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LUMINANCE REQUIREMENTS AND COLOR APPEARANCES OF COLORED DISPLAYS IN TURBID WATER: II. ILLUMINATED AMBIENT VIEWING ENVIRONMENTS

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Contract Number: N00014-74-C-0276
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Prepared for:

Engineering Psychology Programs
Psychological Sciences Division
Office of Naval Research
Arlington, Virginia 22217

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422 Sixth Street
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→ Ten light-adapted observers viewed six narrow-band wavelength displays and a white display through two artificially turbid and illuminated water media. The two water samples were intended to simulate the ambient underwater environment of a near-shore ocean at 20 meters depth and an inshore harbor or bay at 5 meters depth when surface illumination was full sunlight, 10^4 ft-candles. The 'Ocean' simulation was composed of a low concentration of relatively

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large-sized suspensoids illuminated by 17 ft-candles of light spectrally restricted to the green region, 540 nm peak wavelength. The 'Harbor' simulation was composed of a high concentration of relatively small-sized particles in suspension and illuminated by 214 ft-candles of light spectrally restricted in the yellow region, 600 nm peak wavelength.

Against these two backgrounds, observers viewed 2-digit, self-luminous displays which varied in size and color. Observers controlled display luminance to three magnitudes defining three levels of display legibility: 'Minimum', 'Clear' and 'Limit'. At each legibility criterion, observers described the color appearance of the display using a forced-choice, color-naming technique and a restricted set of color-name alternatives: blue, green, yellow, red and white.

The differences in the two underwater viewing environments had significant effects on the two visual tasks. In the 'Ocean' simulation, display luminance required for optimum, 'Clear' legibility was 5.8 ft-L for a 3-mm display at a 25-cm viewing distance; under these same conditions of size and distance, 9070 ft-L of display luminance was required in the 'Harbor' simulation. The color appearances of white, green (552 nm) and yellow (579 nm) displays were qualitatively different in the two environments due to the perceptual phenomenon of chromatic adaptation. Colored displays of short wavelength, 503 nm or less, appeared 'blue' in both environments; long-wavelength displays, 608 nm or more, appeared consistently 'red'.

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ACKNOWLEDGMENTS

This is the fifth in a series of experiments directed to the problem of display design for underwater applications, and sponsored by the Office of Naval Research, Code 455, Engineering Psychology Programs. Dr. Martin A. Tolcott, Director, and Mr. Gerald S. Malecki, scientific officer for this program of research have been continuing sources of encouragement and good counsel. Both the selection of display issues to be addressed and the field implementation of experiments were facilitated by the guidance and support of CAPT J. Barnes, CAPT E. Lyon, III, and CDR I. C. LeMoyne of OPNAV 372G, and by LCDR J. W. Schropp of NAVSEA 00C-DA.

This experiment was carried out using facilities and personnel of COMNAVSPECWARGRU TWO, CAPT N. H. Olson, Commander. The staff of the Test and Support Division coordinated the scheduling of observers from operational units of COMNAVSPECWARGRU TWO, and provided a variety of supports to the project. We are pleased to acknowledge the generous and courteous help of this staff: LT D. T. Coulter, CMTCM J. A. Gay, BMCS J. D. Cozart, GMG1 R. A. Findlay, and GMT3 S. A. Schwarz.

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Mr. Allan Slater, Senior Engineer of Emergency Care Research Institute, Plymouth Meeting, Pennsylvania, designed the test tank, the lamp gantry and the optical system used in the experiment.

Anne S. Mavor did the variance analyses of the luminance data.

We particularly appreciate the help of those officers and enlisted men of SEAL TWO, UDT-21 and UDT-22 who were the experimental observers. Their names are listed in Appendix A of this report.

LUMINANCE REQUIREMENTS AND COLOR APPEARANCES OF COLORED DISPLAYS IN TURBID WATER: II. ILLUMINATED AMBIENT VIEWING ENVIRONMENTS

I. INTRODUCTION

Divers work in a variety of water environments whose characteristics have significant consequences for underwater display design. One particularly important environmental characteristic is turbidity: the sizes and concentrations of organic and inorganic material suspended in the water. Turbidity of natural bodies of water varies widely from relatively clear oceanic waters to moderately turbid near-shore water to heavily turbid inshore rivers, harbors and bays. Effects of turbidity variations on display requirements have been studied in a recent series of experiments wherein dark-adapted observers viewed self-luminous displays through dark, turbid waters (Vaughan, Glass and Williams, 1977, 1978a, and 1978b).

In the present experiment, the simulation of natural underwater viewing environments was broadened to include illuminated, in addition to turbid, waters. Two experimental media were prepared to represent illuminated ocean and harbor waters. 'Ocean' was relatively clear water illuminated by light in the green region of the spectrum; 'Harbor' was very turbid water illuminated by light in the yellow region of the spectrum. Observers' tasks were to determine levels of display luminance required for legibility and to describe the color appearances of the display at several wavelengths. Except for the illumination variable, the experiment was a replication of Vaughan, Glass and Williams, 1978b, so that the effects of dark turbid waters could be compared to illuminated turbid waters as determinants of display luminance requirements and color appearances. The illuminated waters were expected to require higher levels of display luminance for equivalent legibility due to differences in contrast. Dramatic differences were expected in the color appearances of the displays when viewed against spectrally restricted background illumination due to the perceptual phenomenon of chromatic adaptation.

Ambient light in natural bodies of water tends to become monochromatic as depth increases (Tyler, 1959). Daylight at the surface is gradually modified by physical processes of absorption and scattering. Since both processes are wavelength selective, eventually a single or very narrow band of wavelength energy is present, that wavelength to which the type of water is most transmissive. Absorption is the conversion of light to thermal energy, and its effects are a function of wavelength; longer wavelengths are more readily absorbed than shorter wavelengths to a minimum at 480 nm, the wavelength to which clear water is most transmissive (Duntley, 1963). Scattering is the change in direction of travel of light energy due to particles/organisms suspended in the water. Scattering effects are a complex function of particle size, and very small particles selectively scatter shorter wavelengths (Williams, 1970 and 1973). Since oceanic water is relatively clear of scatterers, changes in spectral composition are principally a result of absorption. The wavelengths associated with perception of red, orange, and yellow colors are absorbed within a depth of approximately 20 meters (Reuter, 1971) where the remaining energy is blue-green. In turbid inshore waters both absorption and scattering effects combine to remove the longer wavelengths (red) and the shorter wavelengths (blue) so that, with increases in depth, remaining wavelengths tend toward the yellow region of the spectrum.

The response of the visual system to mono or homochromatic visual fields is to adapt to the hue of the dominant wavelength. Within a few minutes of exposure to a homochromatic background, its color begins to fade toward a neutral gray and the retina is in a state of chromatic adaptation. Under the adapted condition, color appearances of objects in the visual field are systematically altered. Neutral objects (whites and grays) appear the color of the complement of the adapting wavelength and all other colored objects are altered by the perceptual addition of this hue. For example, if visually adapted to green light, white or gray objects appear red (the complement of

green) and other colored objects are perceived as though red had been added to their original hue: e.g., a yellow object will appear orange or even red (Cornsweet, 1970).

Chromatic adaptation to red and blue light has been studied by Kinney and Cooper (1967) using a color-matching technique and low intensity light levels for both background and test stimuli: 0.3426 cd/m^2 (0.1 ft-L). Jacobs and Gaylord, 1967, studied adaptation to red, green and blue light using the color-naming technique of Boynton, Schafer and Neun (1964) and high intensity light levels, 668 cd/m^2 (195 ft-L). Their results showed two general effects of chromatic adaptation on color-name responses to colored light: the relative absence of the hue of the adapting wavelength and the dominance of the hue of the complement to the adapting wavelength. For example, following adaptation to blue light, and regardless of the wavelength of the test stimulus, 'blue' was rarely used to describe the stimulus and the predominant color-name response was 'yellow'.

The phenomenon of chromatic adaptation was apparently experienced by divers during SEALAB I. Divers reported seeing red and yellow objects at an ocean depth of 60 meters; a depth to which no yellow or red wavelength energy could penetrate (Kinney and Cooper, 1967). Since illuminated underwater environments other than the deep ocean tend to be homochromatic, the phenomenon of chromatic adaptation is a potential problem for the use of color as a coding dimension in a range of underwater display applications including submersible consoles and hand-held equipment panels. The present experiment addressed this issue in two illuminated underwater environments typical of Navy diving operations.

II. METHOD

A. Simulation of Illuminated Underwater Environments

Two distinct underwater environments were simulated for use as viewing media: nearshore oceanic water ('Ocean'), and inshore water ('Harbor') during daylight. The two preparations differed widely in their turbidity characteristics and in the intensity and spectral composition of the light by which they were illuminated. The experimental waters were made turbid with uniform latex particles of sizes and concentrations approximating empirically determined modal values for natural oceanic waters (Sheldon, et al, 1972) and for the Chesapeake Bay (Shubel, 1969; Shubel, et al, 1970). Details of the materials and procedures by which the turbidity characteristics were simulated have been described in several previous reports (Vaughan, Glass and Williams, 1977; 1978a, 1978b). As can be seen from Table 1, 'Ocean' turbidity was composed of a relatively low concentration of large-sized scatterers; 'Harbor', a high concentration of small-sized scatterers. Over short-range viewing distances, the optical effects of these turbidity differences were a highly transmissive 'Ocean' indifferent to wavelength, and a wavelength selective and significantly less transmissive 'Harbor'.

Table 1. Particle Sizes and Numbers Defining 'Ocean' and 'Harbor' Turbidity Simulations

	Particle Diameter	Estimated Number of Particles per cm^3 Water
'Ocean'	$\bar{X} = 25.7 \times 10^{-6}m$ $\sigma = 10.0 \times 10^{-6}m$	4.64×10^2
'Harbor'	$\bar{X} = 1.091 \times 10^{-6}m$ $\sigma = 0.0082 \times 10^{-6}m$	7.20×10^6

The artificially turbid waters were prepared in a 70-gallon, plexiglass test tank, and illuminated by fluorescent lamps housed in the ceiling of a wheeled, bridge-like frame or gantry which straddled the test tank. Just beneath the row of lamps was a pair of ledges which ran the full width of the gantry. A removable, clear plexiglass plate was held in place by these ledges; the plate was used as a carrier for acetate sheets of different colors. Variations in luminous output were controlled by number of lamps activated to a limit of twenty; variations in spectral composition of the output were made by combinations of lamp type and color of acetate sheet used to cover the clear plexiglass plate.

Characteristics of the ambient light in the test tank were estimated by taking measurements from the exterior of the plexiglass test tank. A Tektronics, Inc., J16 Photometer-Radiometer was used with a J6511 illuminance probe to measure amount of luminous energy falling on the faceplate through which observers viewed displays. The J16 was used with a J6512 irradiance probe and six cutoff filters to estimate the spectral distribution of the radiant energy in the water. The absorption characteristics of the cutoff filters, the measurements taken and the procedures used to estimate spectral distribution of the ambient light in the experimental viewing media are described in Appendix B. Also described in Appendix B are the assumptions and analytic procedures by which target values of spectral irradiance were determined for each of the simulations.

1. Artificial Daylight in 'Ocean'

The objective of the 'Ocean' simulation was to represent both the total ambient illuminance and the spectral composition of the light energy characteristic of a near-shore ocean at 20 meters depth. The target values for this simulation were based on the optical characteristics of Jerlov's Type 5 water (Jerlov, 1968), and assumed a surface illumination of 10^4 ft-candles which approximates direct sunlight on a clear day. These target values were approximated by a combination of Sylvania 'Daylight' fluorescent lamps (F24T12-D-HO) and green-colored acetate. All twenty lamps were used to

illuminate the 'Ocean' water in the test tank. The average illuminance in the water as measured at locations across the front edge of the test tank was 17 ft-candles. Ambient illuminance in a coastal ocean (Jerlov's Type 5) at 20 meters under direct sunlight is estimated at 25 ft-candles. The spectral distribution of the ambient light in the simulation is shown in Figure 1 and compared to the criterion distribution sought. The figure does not account for differences in total energy between the theoretical and achieved distributions but shows that the available energy in the artificial medium is a close match to the criterion in spectral distribution.

2. Artificial Daylight in 'Harbor'

The objectives for the simulation of ambient light in a harbor were based on optical characteristics of Jerlov's Type 9 water (Jerlov, 1968) a surface illumination of 10^4 ft-candles (direct sunlight) and 5 meters depth. Target value for total illumination was 210 ft-candles.

A combination of sixteen Sylvania 'Warm White' fluorescent lamps (F2412-WW-HO) and a sheet of yellow acetate produced a total ambient illuminance of 214 ft-candles and a spectrally distributed luminous output as shown in Figure 2 and compared to the criterion distribution for the 'Harbor' simulation.

B. Apparatus

Main elements of apparatus used in the experiments included the following:

- Watertight, 70-gallon test tank with drywell.
- Lamp gantry containing 20 fluorescent lamps and an acetate color filter.
- Optical system which presented a 2-digit display, 00-99, at two sizes in seven colors throughout a continuum of luminances.
- Control system by which to select digits for display, and to control and record display luminances.

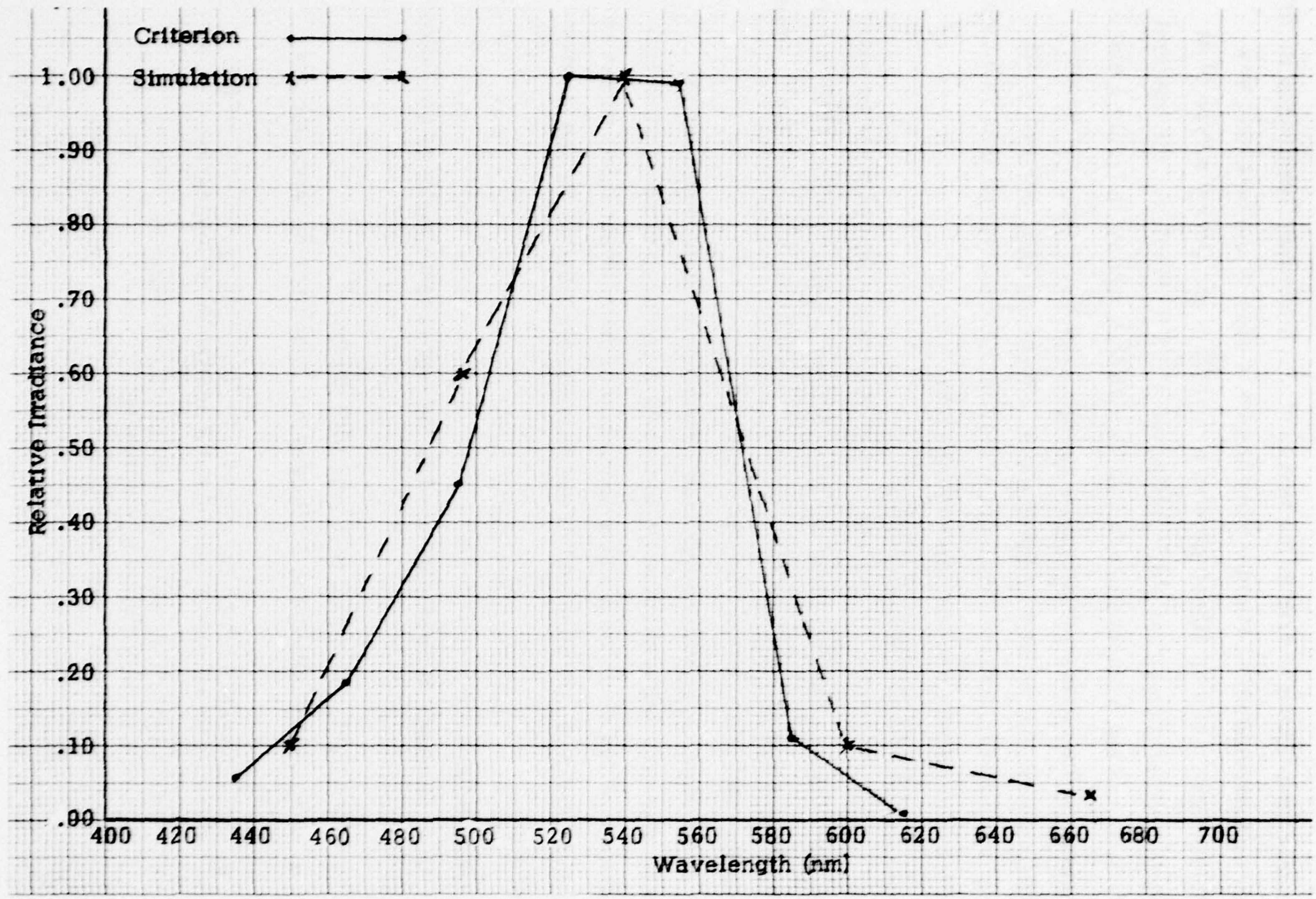

Figure 1. Relative Irradiance per Unit Wavelength: 'Ocean' At 20 Meters Depth

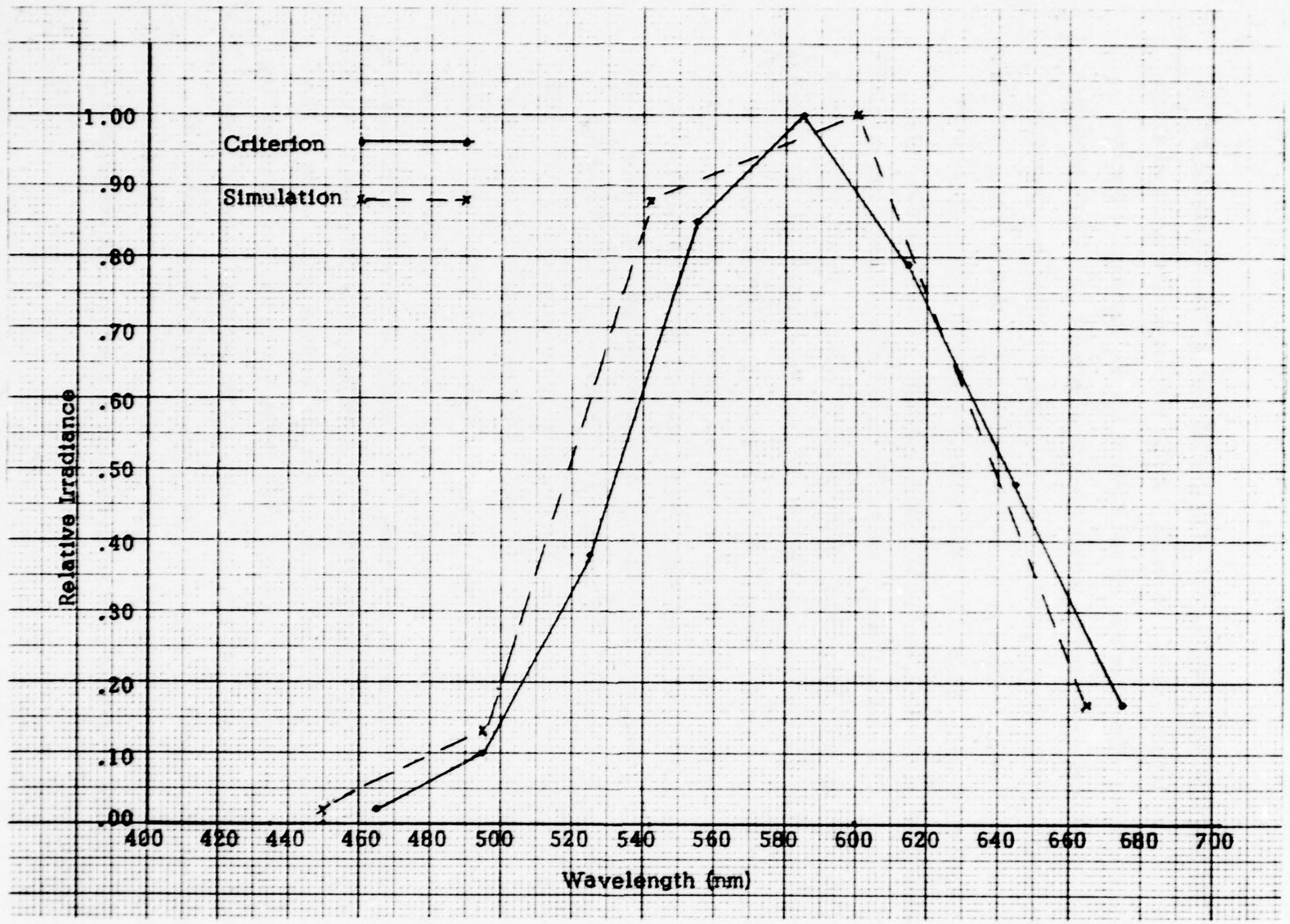

Figure 2. Relative Irradiance per Unit Wavelength: 'Harbor' At 5 Meters Depth

The test tank was constructed of half-inch plexiglass, measured 22" in height, 36" in length and 31" in width. A full facemask was mounted at one end of the tank. The facemask served both to fix the location of the observer's head and eyes, and to introduce optical effects of a glass faceplate at the water/air interface typical of vision through a facemask underwater. A drywell was constructed to fit within the width of the tank and to move along the longitudinal axis of the tank. The forward face of the drywell could be positioned any distance from the faceplate between 5 and 64 centimeters (2-25 inches). The drywell was open at the top so that experimental display variations could be made without waterproofed displays. The optical system was placed into the drywell from the top and the experimenter had easy access to the system by the same means. Further details and illustrations of the test tank and drywell are contained in Vaughan, Glass and Williams, 1977.

The lamp gantry was an aluminum frame constructed to fit over the test tank and to hold the lamps and color-filtering acetates by which water in the tank could be illuminated. The gantry was 32" in width, and cleared the test tank by 1/2" on either side. The height of the gantry was 23-1/2" and cleared the tank top by 1-1/2". The 'roof' of the gantry was 24" in length and 20 fluorescent lamps were packed tightly across the 32" width dimension. An aluminum reflecting plate covered the lamps and served to direct the light downward to the water in the test tank. The twenty lamps were wired in pairs to ten switches so that alternate lamps could be lighted or darkened to control luminance and evenly distribute light across the surface of the water. The height of the lamps was 25" from the base of the gantry and the ledge holding the colored acetate was 24" from the base. A thin but rigid piece of clear plexiglass was used as a carrier for the sheet-acetate filters; it was slid into position along the ledges of the gantry, one inch below the fluorescent lamps. The gantry and its position in relation to the test tank are illustrated in Figure 3.

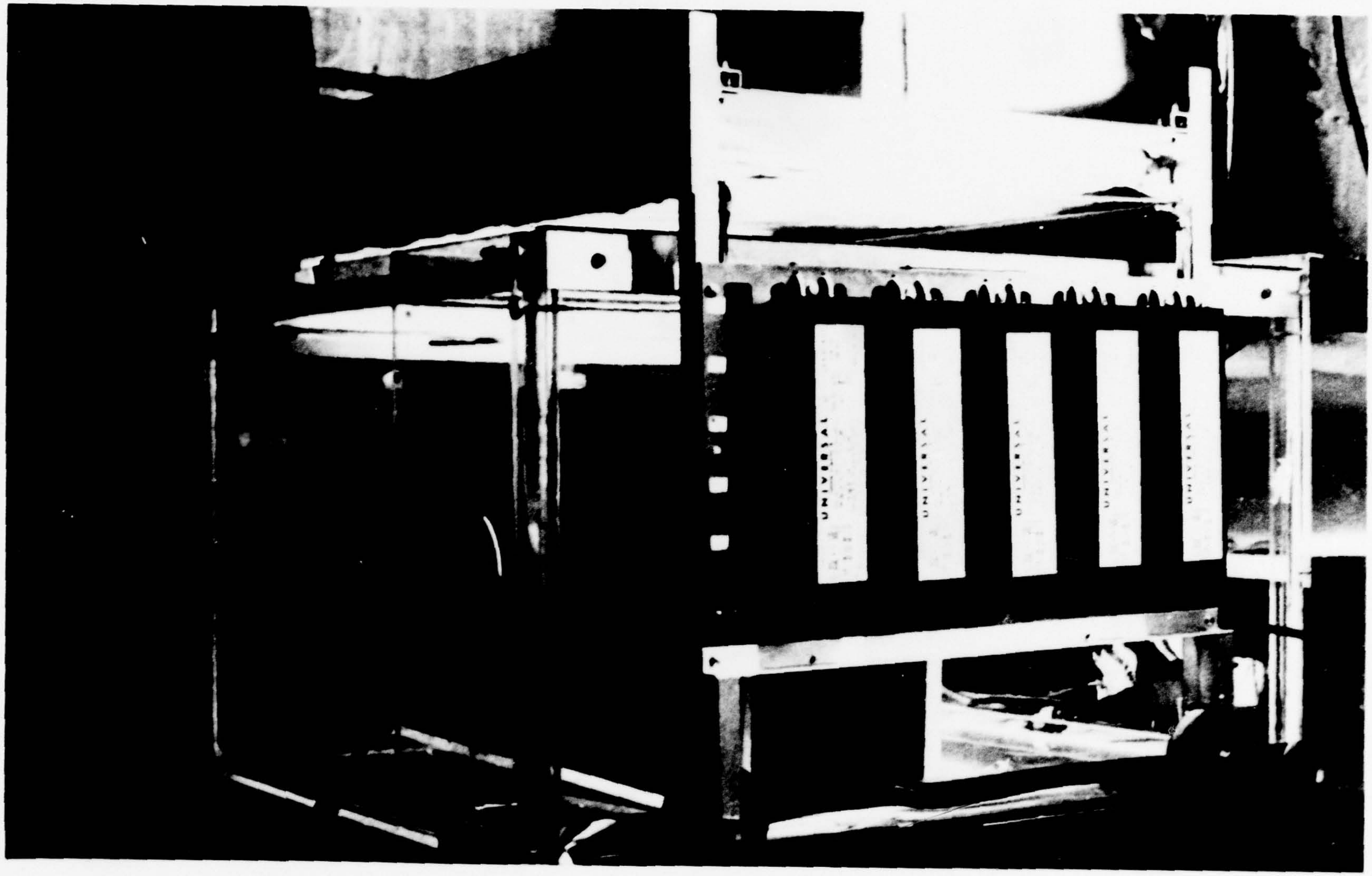

Figure 3. Test Tank and Lamp Gantry

The optical system fit within the drywell and was designed to generate a 2-digit self-luminous display in direct line of sight with the facemask. The light source was a high intensity quartz projector lamp (GE Quartzline Lamp, ELH) whose output was directed to a mirror and from the mirror to a pair of digits which were variable between 00 and 99. Digits were formed by either a full or partial pattern of 21 dots as in commercially available fiber optic displays. The commercial displays were used in the previous experiment (Vaughan, Glass and Williams, 1978b) but their intensity was inadequate for the present application. Consequently, the fiber optic display was simulated by directing very high intensity light through thin aluminum discs drilled with small holes which produced patterns of 'dots' which appeared as digits 0-9. As measured in air with a Spectra Pritchard Photometer Model 1980, MS-80 lens and 6 minute spot covering a single dot, luminance of the unfiltered display was 600,000 ft-L.

In front of the digit templates were a pair of machined slots which held a single color filter, and in front of the color-filter holder a pair of circular, 4-log unit, neutral density wedges by which display luminance was varied. One wedge was positioned manually in order to adjust the luminance of the color filters within a desired range. The second wedge was driven by an electric motor at the rate of one full rotation per minute. The experimenter started the rotation of this wedge which gradually transmitted increased amounts of luminance from the display. The observer stopped the rotation of the wedge by means of a control switch when the display achieved variously defined levels of legibility.

Forward of the neutral density wedges was a reduction lens which could be positioned either in or out of the visual pathway to the display. When the lens was in the pathway, the size of the display was halved.

The optical system is pictured in Figure 4 and the view from the face mask is illustrated in Figure 5.

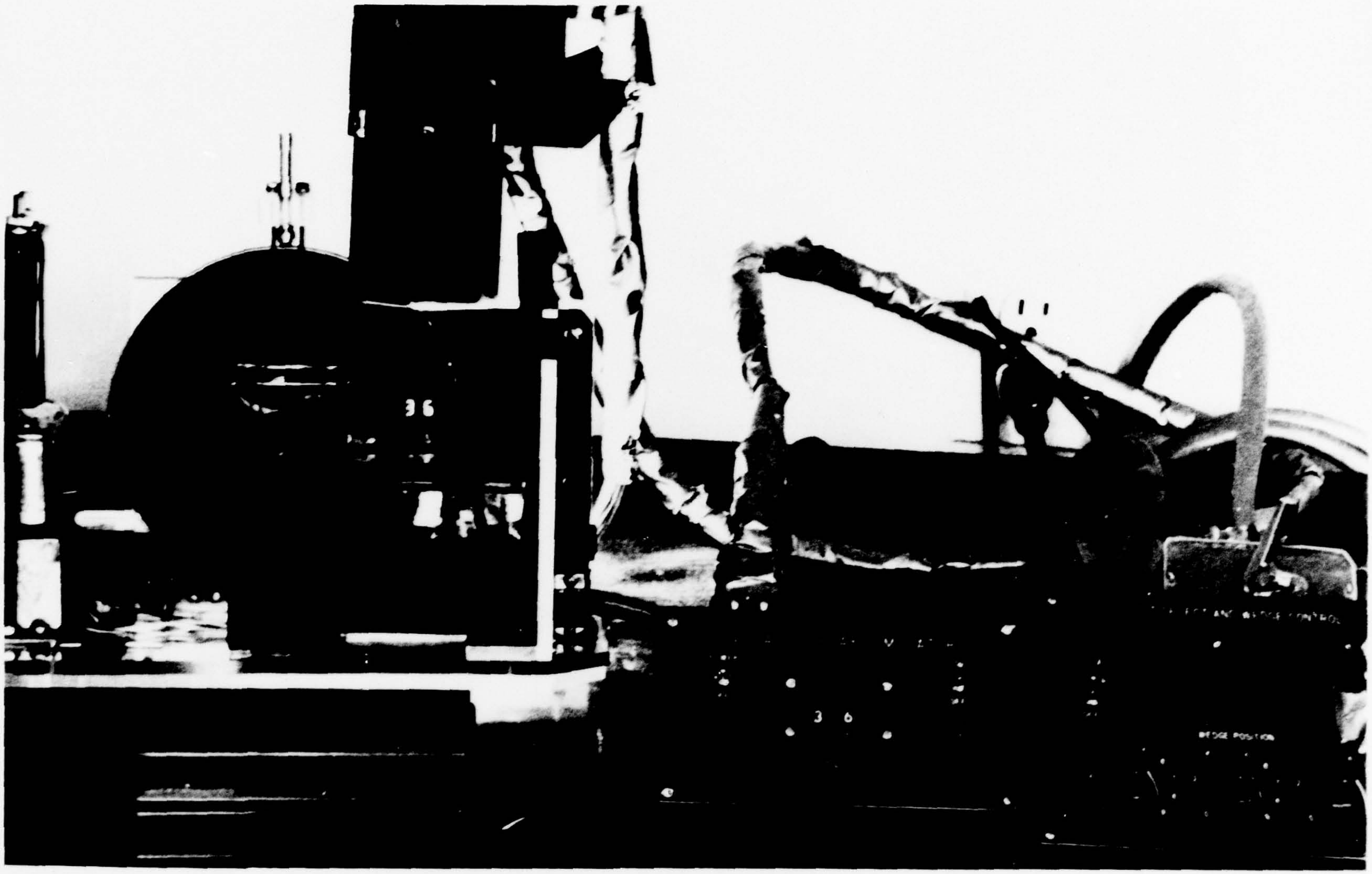

Figure 4. Display, Control and Recording Apparatus

Figure 5. Display As Seen Through the Facemask

C. Observer Characteristics and Tasks

Ten enlisted men and an officer from the operational units of COMNAV-SPECWARGRU TWO participated in the experiment as observers. Their average age was 32 years; range was 25-38. They had 20/20 near acuity measured at 40 cm (16 inches), normal color vision according to the Pseudo-Isochromatic Test Plates of the American Optical Corporation, and an average accommodation near point of 16 cm (6.3"); range was between 10 and 25 cm (4"-10"). Accommodation near point was measured with an R.A.F. Near Point Rule manufactured by Clement Clarke, Ltd.

The experimental tasks of the observers were to establish values of luminance required for legibility of the 2-digit display at three well-defined levels of clarity, and to describe the color appearance of the display at each level of clarity. Legibility and color appearance judgments were made in response to two display sizes at each of seven wavelengths (including white) in both 'Ocean' and 'Harbor' simulations.

D. Dependent Variables

1. Legibility Criteria

Three levels of display clarity were defined based on changes in the appearance of the self-luminous digits as display luminance increased. Initially display luminance was insufficient to be seen at all. As the neutral density wedge rotated and display luminance increased, the digits were seen as composed of irregular lines of dim light forming the digit as a seven-segment line display. With increased luminance the indistinct lines of light were seen as a distinct pattern of dots, each line segment of the digit being composed of three dots. As luminance increased further, the dots became fused again and the digit was seen as composed of overly-bright line segments. These three levels of display clarity were labeled 'Minimum', 'Clear' and 'Limit'. The definitions were identical to those used in the previous study under dark ambient viewing conditions.

2. Color Appearance

As in the prior study (Vaughan, Glass and Williams, 1978b) color appearances of the seven colored stimuli were described by the forced-choice, color-naming method (Boynton, Schafer and Neun, 1964). This procedure restricted observer's response to the use of one or a combination of two color names from a restricted set of five names: 'Blue', 'Green', 'Yellow', 'Red' and 'White'. Responses were scored by awarding a total of three points to the color(s) named per trial. If a single color name was used to describe the color appearance of the display, that color name received all three points. If a two-name combination was used, the name of the dominant color received two points and the secondary color received one point.

E. Display Variations

1. Display Size

The digits of the basic display measured 6.0 mm in height and 4.0 mm in width. When the reduction lens was positioned to intercept the visual pathway, the dimensions were halved to 3.0 mm and 2.0 mm. In the 'Ocean' simulation, display size was varied at two levels: 41' and 23' visual angle by positioning the drywell at 25 cm and 45 cm from the facemask and using the reduction lens. This procedure confounded the effects of display size and viewing distance in order to obtain a significantly smaller visual angle. In the 'Harbor' turbidity, display size was varied at 41' and 82' visual angle by using the two display sizes at one viewing distance, 25 cm.

2. Display Wavelength

Six narrow-band wavelengths and a white display were produced by appropriate filters. The narrow-band, glass interference filters were obtained from Bausch and Lomb, Inc., of Rochester, New York. Their transmission characteristics are presented in Table 2. The white display condition was produced by inserting in front of the basic display a blue acetate filter: Roscolux No. 62, Booster Blue.

Table 2. Transmission Characteristics of the Interference Filters

Peak Wavelength	Percent Transmission at Peak Wavelength	Half-Band Pass (Bandwidth at 50% Transmission)
473 nm	43%	468-478 nm
503 nm	43%	498-508 nm
552 nm	35%	548-556 nm
579 nm	38%	575-583 nm
608 nm	38%	603-613 nm
640 nm	44%	635-645 nm

The narrow-band filters reduced the total energy of the basic display by varying amounts and established the upper limit of luminance that could be experimentally produced at each wavelength. The Roscolux acetate filter had much less of an effect, and in order to adjust its upper limit to the others, the second neutral density wedge was used. Resulting limits on display luminance for each filter are presented in Table 3.

Table 3. Luminance Limit for Each 'Color' Filter

Filter	Luminance Limit (ft-L)
473 nm	2,350
503 nm	9,850
552 nm	25,000
579 nm	26,800
608 nm	29,000
640 nm	17,280
White	27,500

The neutral density wedge at its most opaque position reduced the luminance of each color filter maximum by 4 log units and during its rotation gradually permitted the luminance to return to its maximum. Since each color filter had a different maximum luminance, a given position of the wedge produced a unique luminance for each color filter. The function of luminance with wedge position was determined for each color filter by the following procedure. Wedge position was defined by angular rotation of the shaft on which the wedge was mounted. Full 360° shaft rotation was divided into units between 000 (most opaque) to 830 (clear glass). Shaft rotation was sensed by a potentiometer and the value displayed by digital readout. With each color filter in place, measurements of photopic luminance were made with a Spectra Pritchard Photometer Model 1980 at each of 50 wedge positions between 000 and 830. The measurements were processed by a computer program which interpolated luminance values for all intermediate wedge positions. The program produced a tabled printout of luminance-by-wedge position for each color filter.

F. Experimental Design and Procedure

The experimental design model was a 2 x 2 x 7 factorial design with repeated measurements (Winer, 1962). Seven colored displays were presented at two sizes in two illuminated/turbid visual environments. Except that in the present experiment observers were light-adapted, details of the design and data collection procedure were identical to those in the previous experiment with dark-adapted observers (Vaughan, Glass and Williams, 1978b).

Data were collected from ten observers using the 'Harbor' viewing medium during 22-26 January, 1979; using the 'Ocean' environment during the interval 5-9 February 1979. Table 4 is an outline of the 2 x 2 x 7 experimental design. Within each viewing environment, display-size order effects were counterbalanced among observers, and presentation order of the seven colored displays was randomized for each observer. In order to control

Table 4. Experimental Design Outline

Color Filter (nm) \ Display Size	'Ocean'		'Harbor'	
	3 mm at 45 cm or 23'	3 mm at 25 cm or 41'	3 mm at 25 cm or 41'	6 mm at 25 cm or 82'
473				
503				
552				
579				
608				
640				
White				

whole-display luminous output per trial, only those digits composed of a 15-dot pattern (2, 3, 5, 6 and 9), were used in randomized pairs.

Observers were screened for 20/20 near acuity, normal color vision and accommodation near point within 25 cm; briefed about the purpose of the experiment, their experimental tasks, and the definitions of 'Minimum', 'Clear' and 'Limit' legibility; and practiced in the procedure to be used in the experimental trials. Observer was then light-adapted for five minutes by looking at the illuminated water. The inter-trial re-adaptation interval was also of five minute duration — an interval selected on the basis of the work of Kinney and Cooper, 1967.

Data trials were run according to the following procedural steps:

- Experimenter set up the display size/color filter combination and indicated, 'Ready'.
- Observer put his face into the full facemask, and experimenter initiated rotation of the neutral density wedge.
- Observer stopped wedge at 'Minimum' legibility criterion, and experimenter recorded wedge position.
- Observer described color appearance of the display as one, or an ordered combination of two color names from the restricted set; experimenter recorded the color name(s) given.
- Experimenter continued the rotation of the wedge and observer stopped the wedge at the 'Clear' legibility criterion and described the color appearance; experimenter recording wedge position and color name(s) associated with 'Clear' legibility.
- Continuation of the procedure through 'Limit' legibility criterion. End of trial. Experimenter reset the wedge to its start position (fully dark) and observer re-light-adapted for 5 minutes.

G. Data Analyses and Statistical Tests

The luminance data were analyzed in the paradigm of a 2-factor (display size and wavelength), repeated measures analysis of variance. A risk criterion of $p < .01$ was used to evaluate results of the analyses since the repeated measures design, by minimizing the effects of differences among individual observers, is particularly efficient in detecting differences between main effect variables such as display size and wavelength. The omega squared ($\hat{\omega}^2$) statistic (Hays, 1973) was computed for each significant effect as an estimate of the proportion of total variance in luminance responses accounted for by the effect variable.

Variance analyses were conducted within the water conditions at each level of legibility. Differences in values of luminance required for legibility in the two illuminated waters were so great (3.5 log units), due to differences in turbidity and in background luminance, that statistical comparisons between the two water conditions were not made. For example, mean display

luminance required for 'Minimum' legibility was 1.0 ft-L in the 'Ocean' at 17 ft-candles ambient illuminance *vs* 3500 ft-L in the 'Harbor' at 214 ft-candles ambient illuminance.

Analysis of the color-name scores followed the procedure previously used in the experiment with dark viewing environments. Each of the seven colored displays was described in color appearance under various combinations of water type, display size and display luminance. 'Color appearance' was defined by the distribution of responses across the five color names permitted: blue, green, yellow, red, white. Since each of ten observers allotted 3 'points' per trial, the aggregated response distribution was based on a total of thirty 'points'. The several combinations of viewing conditions were compared (re: effects of the conditions on color appearance) by treating the thirty 'points' as if they were frequencies, and testing the distributions for significance of difference using the Chi-Square Test. The effects of this procedure are to artificially enlarge the sample size from ten to thirty and to introduce dependence between pairs of score distributions tested. These procedures compromise the Chi-Square Test, and its application here is intended as an aid to simple inspection as a means for identifying potentially important differences in the color appearance of colored displays as conditions of the underwater viewing environment change.

III. RESULTS

A. Display Luminance Requirements*

1. In An Illuminated 'Ocean'

Self-luminous displays were viewed by light-adapted observers against a background of 17.0 ft-candles of ambient illuminance, spectrally limited to green light. Levels of display luminance required for legibility were determined for two display sizes of seven colors at three levels of clarity. The analysis of variance summary tables (Table 5) show that required luminance was significantly affected by differences in display size at all three levels of legibility. The main effect of display size was both significant according to the statistical test and accounted for large proportions of the total response variance (.41, .40 and .20 at 'Minimum', 'Clear' and 'Limit levels of legibility). Table 6 shows the mean luminance values required for the several combinations of display size and display clarity. The larger display size required significantly less luminance than the smaller at each of the three levels of legibility. The general effect of display size differences was approximately a 0.5 log unit of luminance at each level of display clarity; the effect of legibility differences was an approximately 0.75 log unit of display luminance between successive categories.

The effect of display color variations on luminance requirements was ambiguous. Display color had no significant effect at either 'Minimum' or 'Clear' legibility; at 'Limit' legibility, however, color was a significant main effect and the color x size interaction was also significant according to the statistical criterion. The proportion of response variance accounted for

*Reported values of display luminance are as measured in air at the display source; not at the eye of the observer. Raw data are tabled in Appendix C.

Table 5. ANOVA Summary Tables for Factors Affecting Display Luminance Requirements in An Illuminated 'Ocean'

1. At 'Minimum' Legibility: Seven Display Colors, Two Sizes

Source	df (Source, Error)	MS_s/MS_e	F	p	$\hat{\omega}^2$
Color	6, 54	1.55/.79	1.96	NS	
Size	1, 9	94.96/1.09	87.12	< .01	.41
Color x Size	6, 54	1.71/.55	3.11	NS	

2. At 'Clear' Legibility: Seven Display Colors, Two Sizes

Source	df (Source, Error)	MS_s/MS_e	F	p	$\hat{\omega}^2$
Color	6, 54	78.76/31.94	2.47	NS	
Size	1, 9	4429.69/109.75	40.36	< .01	.40
Color x Size	6, 54	44.37/15.13	2.93	NS	

3. At 'Limit' Legibility: Six Display Colors, Two Sizes

Source	df (Source, Error)	MS_s/MS_e	F	p	$\hat{\omega}^2$
Color	5, 45	13226.40/3590.58	3.68	< .01	.08
Size	1, 9	129089.00/7661.44	16.85	< .01	.20
Color x Size	5, 45	8514.00/1662.33	5.12	< .01	.06

Table 6. Display Luminance (ft-L) Required for Legibility of Small- and Large-Sized Displays in An Illuminated 'Ocean'

Display Size	Legibility Criterion		
	'Minimum'	'Clear'	'Limit'
23' visual angle 3 mm digits at 45 cm distance	2.6	17.1	115.8
41' visual angle 3 mm digits at 25 cm distance	1.0	5.8	45.8

by display color differences, however, was small (.08 and .06) and results should be regarded with caution.

Tests were made between individual pairs of display colors in order to uncover the sources of the significant color effects. The statistical procedure used was the t test as applied to matched groups (see Edwards, 1950, p. 276). None of the differences between color pairs was significant when the display was 23' visual angle. At 41' visual angle, however, the tests separated the seven colors into three subsets with respect to luminance defining the upper boundary of display legibility: high, medium and low. The white display had a high-luminance upper bound, 95 ft-L; the mid-range wavelengths 503, 552 and 579 nm had medium-luminance upper bounds, 32-47 ft-L; and the longer-wavelength displays, 608 nm and 640 nm had low-luminance upper boundaries, 27 ft-L.

2. In An Illuminated 'Harbor'

The colored displays were viewed in the substantially more turbid 'Harbor' water against an ambient illumination of 214 ft-candles, spectrally compressed in the yellow region with a maximum at 600 nm. In this viewing medium, display luminance values were determined for 'Minimum' and 'Clear' levels of legibility but not for 'Limit' legibility. All displays were seen as

'Clear' to their maximum value of luminance. The analysis of variance summary tables (Table 7) show display size as a significant determinant of display luminance. Size differences accounted for 28% and 37% of the response variance at 'Minimum' and 'Clear' legibility levels. Table 8 presents the mean values of luminance required for legibility at two display sizes and two levels of clarity.

Table 7. ANOVA Summary Tables for Factors Affecting Display Luminance Requirements in An Illuminated 'Harbor'

1. At 'Minimum' Legibility: Seven Display Colors, Two Sizes

Source	df (Source, Error)	MS_s/MS_e	F	p	$\hat{\omega}^2$
Color	6, 54	10562550/1619833	6.52	< .01	.12
Size	1, 9	120888920/1758507	68.75	< .01	.28
Color x Size	6, 54	2176005/1391587	1.56	NS	

2. At 'Clear' Legibility: Six Display Colors, Two Sizes

Source	df (Source, Error)	MS_s/MS_e	F	p	$\hat{\omega}^2$
Color	5, 45	23317286/8392093	2.78	NS	
Size	1, 9	709938866/9701286	73.81	< .01	.37
Color x Size	5, 45	8063276/6043700	1.33	NS	

Table 8. Display Luminance (ft-L) Required for Legibility of Small- and Large-Sized Displays in An Illuminated 'Harbor'

Display Size	Legibility Criterion	
	'Minimum'	'Clear'
41' visual angle 3 mm digits at 25 cm distance	3536	9070
82' visual angle 6 mm digits at 25 cm distance	1377	4190

Variations in display color had a significant effect on display luminance required for 'Minimum' legibility, and accounted for 12% of the total response variance. Since the color x size interaction was not statistically significant, the two display sizes were combined and individual pairs of display colors were tested for significance using the mean luminance values. The results of these tests (t-tests between matched pairs) showed that the blue display (473 nm) required significantly less luminance for 'Minimum' legibility than all other display colors; mean luminance for the 473 nm display was 1069 ft-L vs a mean of 2513 ft-L for the other six displays. No other differences between pairs of colored displays were significant. At 'Clear' legibility, color was not a significant determinant of display luminance.

B. Display Color Appearances*

1. In A Chromatically Green 'Ocean'

The color appearances of six narrow-band wavelength displays and a white display were described by ten observers who were chromatically adapted to green light of 540 nm peak wavelength. Their responses were restricted to five color names (blue, green, yellow, red, white), but they had the option of using either a single color name or a combination of any

*Raw data are tabled in Appendix D.

two color names to describe their perceptual experiences. The seven colored displays were presented at two sizes and at three levels of luminance which defined successive legibility criteria: 'Minimum', 'Clear' and 'Limit'.

The strategy for analyzing the color-name data was to select one combination of display luminance and size as a standard for describing the color appearance of each display wavelength, and then to examine variations in the size and luminance variables for potentially significant differences in the standard color appearances. In the 'Ocean' simulation, the largest display size (41' visual angle) at the optimal level of legibility ('Clear') was the combination used as a standard for describing color appearance.

The color appearance of a given display was defined by a proportionate distribution of the thirty scores awarded to the five color names. On any one trial, a single color name given in response to a stimulus was scored 3; a combination of two color names was scored 2 for the dominant color and 1 for the secondary color. When aggregated over the ten observers, each proportionate distribution was based on 30 scores.

Table 9 shows the proportion of total scores given each of five color-name categories for the seven wavelength-controlled displays. The displays are listed according to their dominant wavelength in the columns of the table; the color-name response categories are the rows of the table. Cell entries define the proportion of the 30 scores accounted for by the color name of the row when observers described the stimulus in the column. From Table 9, the color perception of each stimulus was inferred from the proportionate score distribution. The white display was seen as 'Red-white'; 473 nm, 'Blue'; 503 nm, 'Blue'; 552 nm, 'White'; 579 nm, 'Red-white; 608 nm, 'Red'; and 640 nm, 'Red'.

Each of the seven colored displays was described at three levels of luminance, 1.0 ft-L, 5.8 ft-L, and 45.8 ft-L. These luminance values defined the lower ('Minimum'), optimal ('Clear') and upper ('Limit') limits of display legibility. The color-name distributions at the upper and lower boundaries

Table 9. Proportionate Distribution of Color-Name Scores Given in Response to Seven Colored Displays Viewed in An Illuminated 'Ocean'

Color Names	Display Wavelength (nm)						
	White	473	503	552	579	608	640
Blue		.93	.80	.03			.03
Green		.03	.10	.10			
Yellow				.10	.20		
Red	.70			.10	.50	1.00	.97
White	.30	.03	.10	.66	.30		

of luminance were compared to the distribution at the optimal value ('Clear' legibility) and tested for significance of difference with Chi-Square. Three of the seven colored displays were judged to shift in color appearance as a function of luminance differences: White, 552 nm and 579 nm.

The white display became progressively more 'White' and less 'Red' as luminance increased. At 1.0 ft-L the white display was seen as principally 'Red'; at 5.8 ft-L as 'Red-white', and at 45.8 ft-L the display was more frequently called 'White'. The 2 x 3 Chi-Square was 12.90, df = 2, and $p < .005$.

The 552 nm display was perceived principally as 'White' at the 1.0 and 5.8 ft-L luminances and 'White-yellow' at the limit of legibility, 45.8 ft-L. The Chi-Square was 11.70, df = 4 and $p < .025$.

The 579 nm display was seen as principally 'Red' at 1.0 ft-L, and shifted toward 'Yellow' or a low-saturation red ('Red-white') at 5.8 ft-L and then to 'White-red" at 45.8 ft-L. The 3 x 3 Chi-Square was 9.9, df = 4 and $p < .05$.

Proportionate shifts in color-name score distributions for these three colored displays are illustrated in Figures 6, 7 and 8.

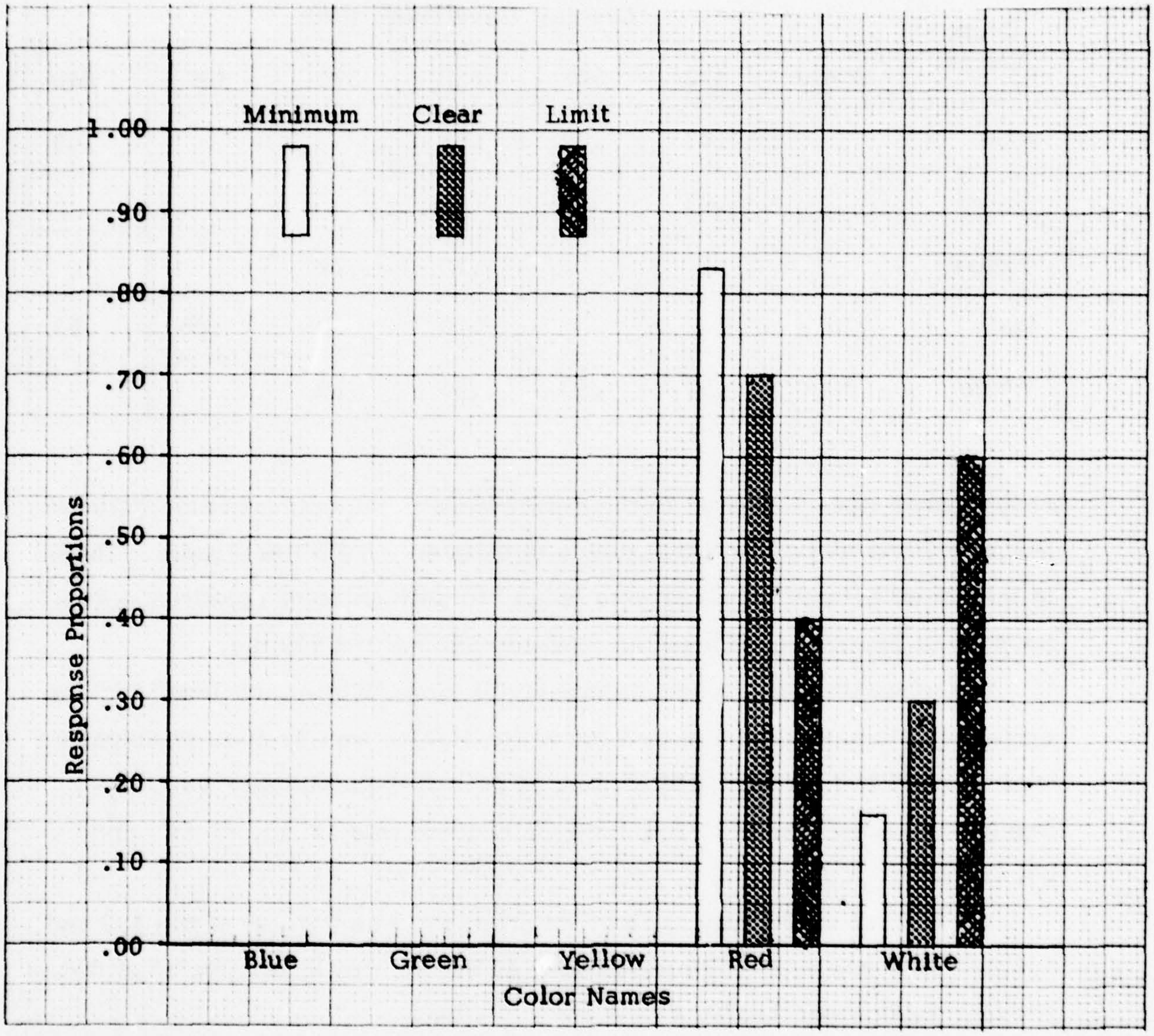

Figure 6. Distribution of Color-Name Scores in An Illuminated 'Ocean' At Three Levels of Display Legibility: White Display

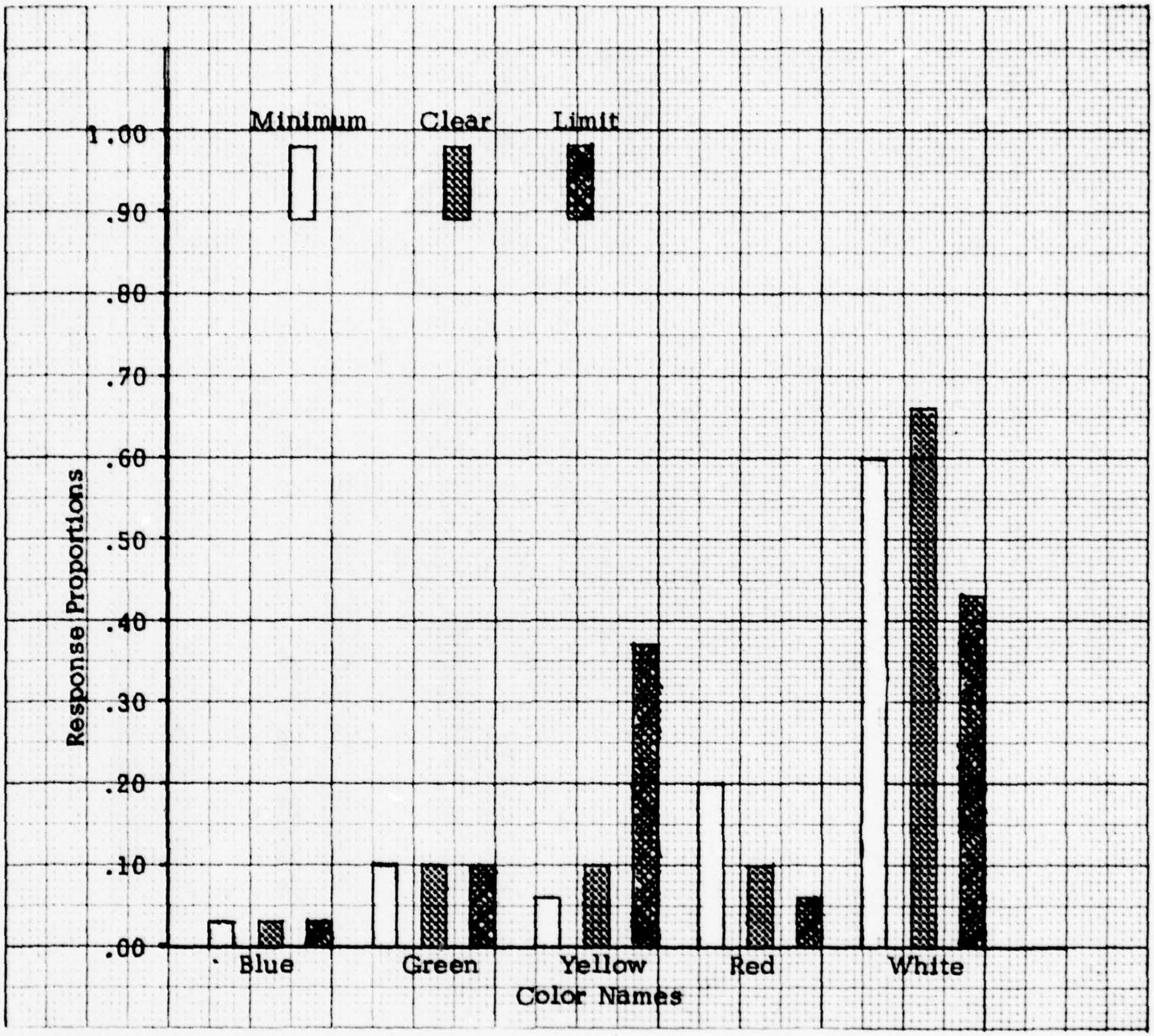

Figure 7. Distribution of Color-Name Scores in An Illuminated 'Ocean' At Three Levels of Display Legibility: 552 nm Display

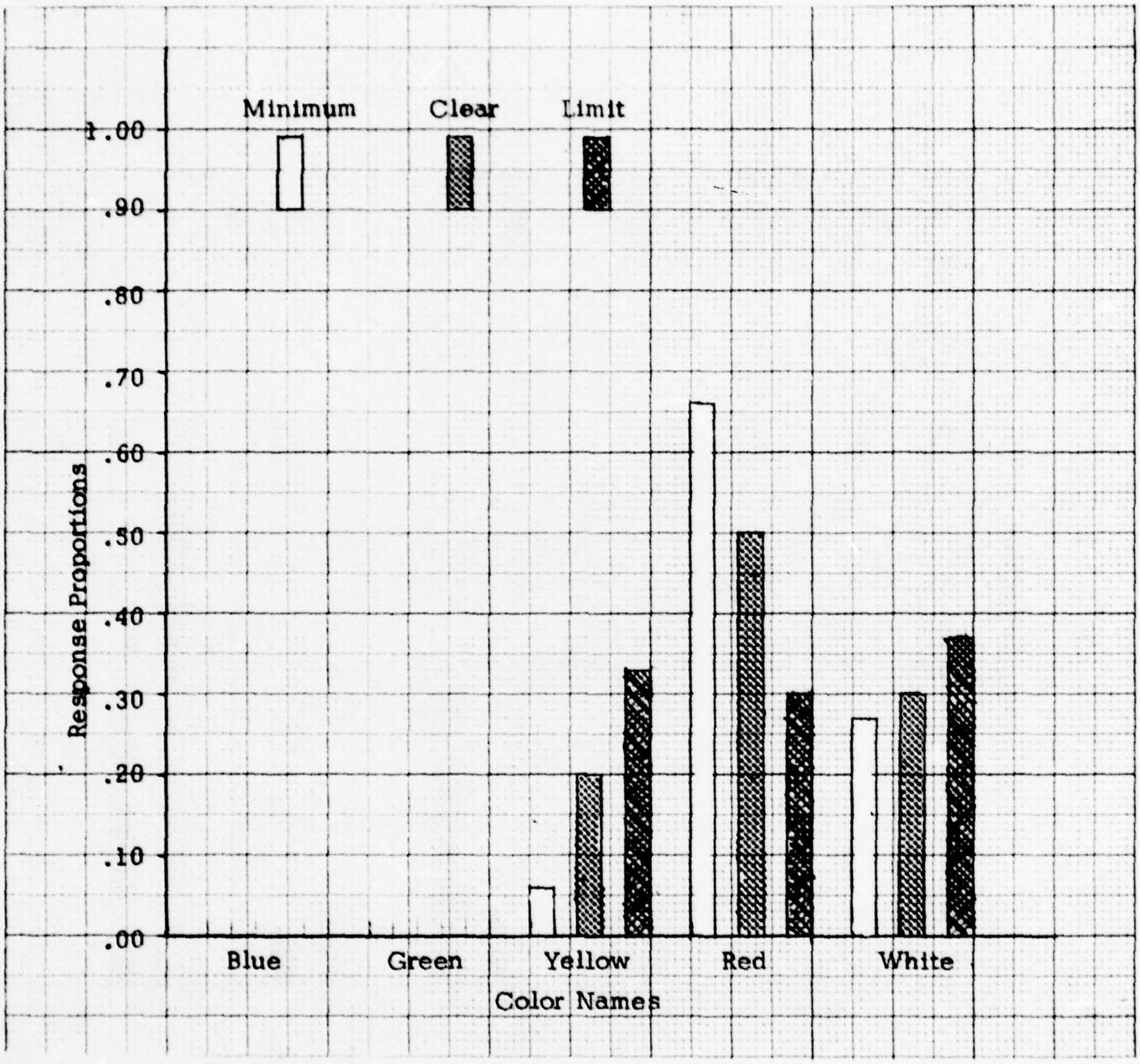

Figure 8. Distribution of Color-Name Scores in An Illuminated 'Ocean' At Three Levels of Display Legibility: 579 nm Display

Four of the seven colored displays were unaffected by variations in luminance: the two short-wavelength displays, 473 nm and 503 nm, were called 'Blue' and the two long-wavelength displays, 608 nm and 640 nm, were called 'Red'. Table 10 illustrates the color name most likely to be associated with the seven stimuli at each of three levels of display legibility.

Display size was examined as a main effect on color appearance by comparing color-name score distributions for each stimulus at 23' vs 41' visual angle at the 'Clear' legibility level (5.8 ft-L). No differences were significant according to the Chi-Square Test.

Table 10. Color Appearances of Seven Colored Displays At Three Levels of Legibility Viewed in An Illuminated 'Ocean'

Display Wavelength	Legibility Criterion		
	'Minimum'	'Clear'	'Limit'
White	Red	Red-white	White-red
473 nm	Blue	Blue	Blue
503 nm	Blue	Blue	Blue
552 nm	White	White	White-yellow
579 nm	Red	Red-white	White-red
608 nm	Red	Red	Red
640 nm	Red	Red	Red

2. In A Chromatically Yellow 'Harbor'

Observers described the color appearances of seven colored displays at all combinations of two sizes, 41' and 82' visual angle, and two luminances, 3536 and 9070 ft-L, which defined 'Minimum' and 'Clear' legibility. None of the colored stimuli could be made sufficiently bright to be seen according to the criterion for 'Limit' legibility. The background illuminance of the 'Harbor' simulation was 214 ft-candles and the spectral composition of the ambient light was concentrated in the yellow region with a peak energy at 600 nm.

Standard color appearance of each colored display was defined by the distribution of color-name scores when the large-sized display was at the luminance required for 'Clear' legibility. Table 11 shows the proportionate distribution of color-name scores; Table 12 describes the color appearance of each display as inferred from the color-name scores.

Potential effects on color appearance of differences in display size and in luminance were tested using the Chi-Square Test. All comparisons were insignificant, suggesting that in an illuminated 'Harbor', color appearances were not affected by the size and luminance differences included in the experiment.

Table 11. Proportionate Distribution of Color-Name Scores Given in Response to Seven Colored Displays Viewed in An Illuminated 'Harbor'

Color Names	Display Wavelength (nm)						
	White	473	503	552	579	608	640
Blue	.37	.97	.93	.16		.03	.10
Green				.77	.10		
Yellow	.03				.13		
Red	.23	.03				.83	.90
White	.37		.06	.06	.77	.13	

Table 12. Color Appearances of Seven Colored Displays At 'Clear' Legibility Viewed in An Illuminated 'Harbor'

Display Wavelength	Color Appearance
White	Blue-white
473 nm	Blue
503 nm	Blue
552 nm	Green
579 nm	White
608 nm	Red
640 nm	Red

IV. SUMMARY AND APPLICATION OF RESULTS

Two distinctly different illuminated underwater environments were simulated. The simulations represented both the turbidity conditions and the ambient light at 5 meters in a turbid inshore harbor or bay, and at 20 meters in a near-shore ocean. Consequently, displays were viewed against qualitatively different backgrounds: the 'Ocean' viewing medium was a moderate illuminance of 17 ft-candles spectrally concentrated in the green region; the 'Harbor' medium was 214 ft-candles and spectrally yellow. The effects of these environmental differences on display luminance requirements and on color appearances of colored displays were correspondingly large. Display luminance requirements were on the order of 3.5 logarithmic intervals apart for a comparable display size and legibility criterion. Color appearances of colored displays were altered dramatically and predictably according to the perceptual phenomenon of chromatic adaptation.

A. Environmental Differences Affect Luminance Requirements

Figure 9 locates the several combinations of experimental conditions on a logarithmic scale of luminance (ft-L). The entire range of display luminance requirements for the 'Ocean' environment was contained within the range 1.0 to 115.0 ft-L; while the 'Harbor' environment required 1377 ft-L for its least demanding combination of conditions, a large-sized display at 'Minimum' legibility. The demands of the two environments cannot be fully compared since in the 'Harbor' the upper boundary ('Limit' legibility) was not determined; at 27,000 ft-L the displays were seen as 'Clear' and undistorted. The range of display luminance for 'Minimum' and 'Clear' legibility conditions, however, was 1.0 to 17.0 ft-L in the 'Ocean' and 1377 to 9070 ft-L in the 'Harbor'.

Figure 9 further shows that in the 'Ocean' viewing environment luminance requirements were regular functions of display size and legibility criterion. Step intervals between display sizes were slightly less than 1/2 log unit luminance; between legibility criteria, approximately 3/4 log unit.

Color of the display had a significant effect on luminance requirements in one combination of conditions. In the 'Harbor' simulation, where observers were

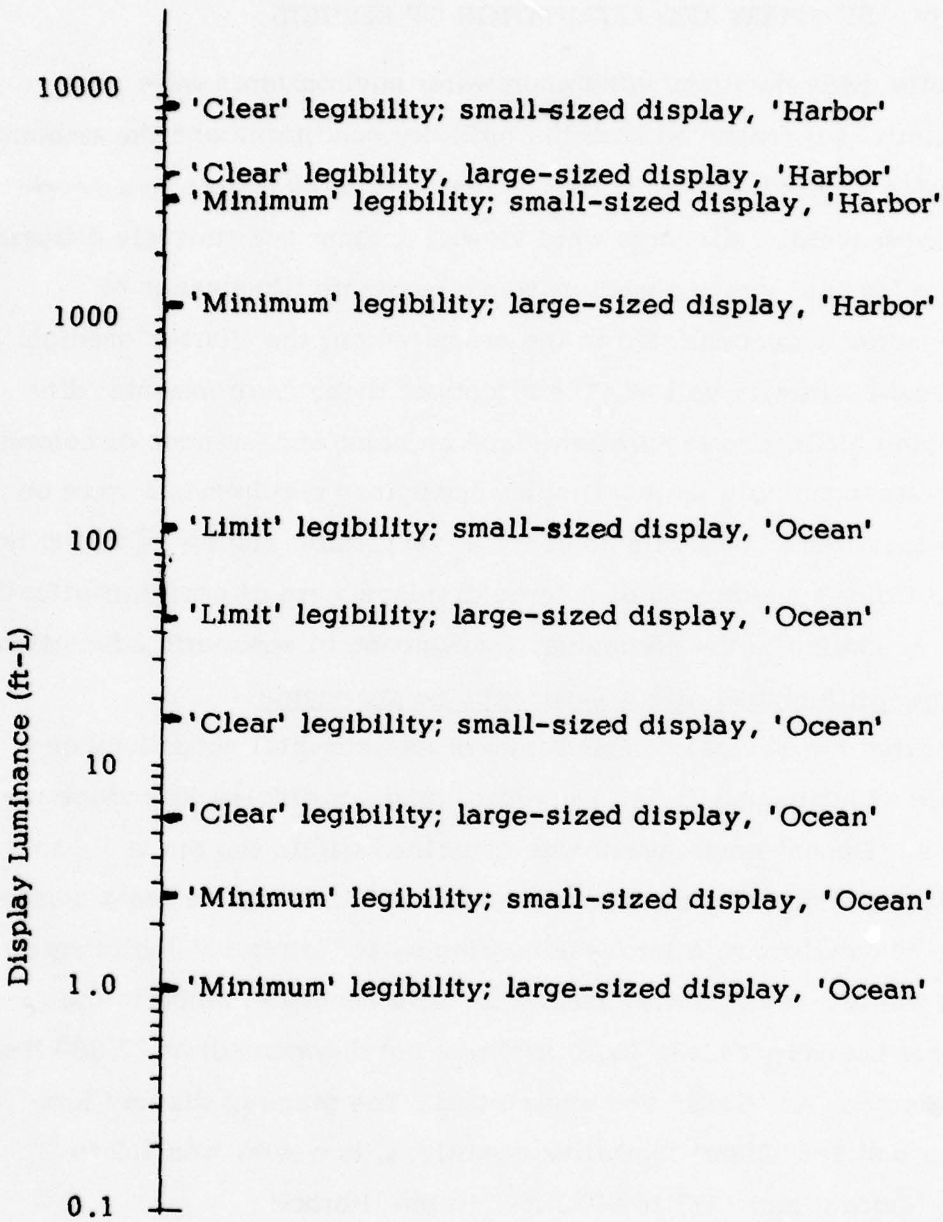

Figure 9. Display Luminance Requirements (ft-L) for Combinations of Experimental Conditions

adapted to a surround of yellow light at 214 ft-candles of illuminance, a blue display (473 nm) required less luminance for legibility at the 'Minimum' criterion than any other colored display. The difference in required display luminance was on the order of 1000 ft-L for the blue (473 nm) display vs 2500 ft-L for the other colors. This result is attributable to the effect of the adapting wavelength on the response characteristics of the eye's color receptors; the effect of the yellow ambient light is to reduce the sensitivity of red and green receptors relative to the blue receptors (see Wald, 1964).

A similar, although not statistically significant effect was present in the 'Ocean' simulation where adaptation to green ambient light presumably reduced the sensitivity of blue and green receptors relative to red. Both of the red-appearing displays (608 and 640 nm) required less luminance for 'Minimum' legibility than did the remaining colors. However, at the low level of ambient illuminance (17 ft-candles) the magnitude of the adaptation effect was not sufficient to produce a statistically reliable difference.

B. Environmental Differences Affect Color Appearances

The ambient light in each water medium was spectrally restricted in different regions: green in the 'Ocean' simulation and yellow in the 'Harbor'. Observers were chromatically adapted to the dominant environmental color, and the colored self-luminous displays were modified in appearance by this perceptual effect. The white, green (552 nm) and yellow (579 nm) displays were most dramatically altered in color appearance in the two illuminated environments. The white display appeared 'Red-white' in the 'Ocean' and 'Blue-white' in the 'Harbor'. The 552 nm display appeared 'White' in the 'Ocean' and 'Green' in the 'Harbor'. The 579 nm display appeared 'Red-white' in the 'Ocean' and 'White' in the 'Harbor'.

Displays whose characteristic wavelength was toward the extremes of the visible spectrum were not significantly different in color appearance in the two environments. The 473 nm and 503 nm displays were seen as 'Blue' in both 'Ocean' and 'Harbor' simulations. In the 'Ocean', the effects of chromatic adaptation to green was to neutralize the green component of these displays; in the 'Harbor' chromatic adaptation to yellow had the effect of adding blue to their normally 'Bluish' appearance. The longer wavelength displays, 608 nm and 640 nm, were seen as 'Red' in both environments. When adapted to the green 'Ocean', the complement (red) was added to the normally reddish appearance of these wavelengths, and when adapted to yellow in the 'Harbor' the normal yellow component of the 608 nm display was neutralized.

Figures 10, 11 and 12 compare the color-name score distributions in 'Ocean' vs 'Harbor' for the white, 552 nm and 579 nm displays. Table 13 lists the color name or combination of color names most typical of observer responses in the two environments.

C. Operational Applications

Daylight-illuminated nearshore oceans and inshore harbors/bays are uniquely different underwater visual environments. Visual displays designed for one environment will be more or less incompatible with the other. The present experiment simulated the ambient light at 20 meters depth in a near-shore ocean and at 5 meters depth in a harbor/bay. The luminance required for a clearly legible, self-luminous display in the former environment was 6 ft-L, and in the latter, 9000 ft-L as measured at the display source. Those values were for a 3-mm digit at a 25 cm viewing distance (41' visual angle); doubling the display size reduced the required luminance by approximately 0.5 log unit.

Because of the combined effects of absorption by the water and scattering by particles suspended in the water, daylight tends to become monochromatic

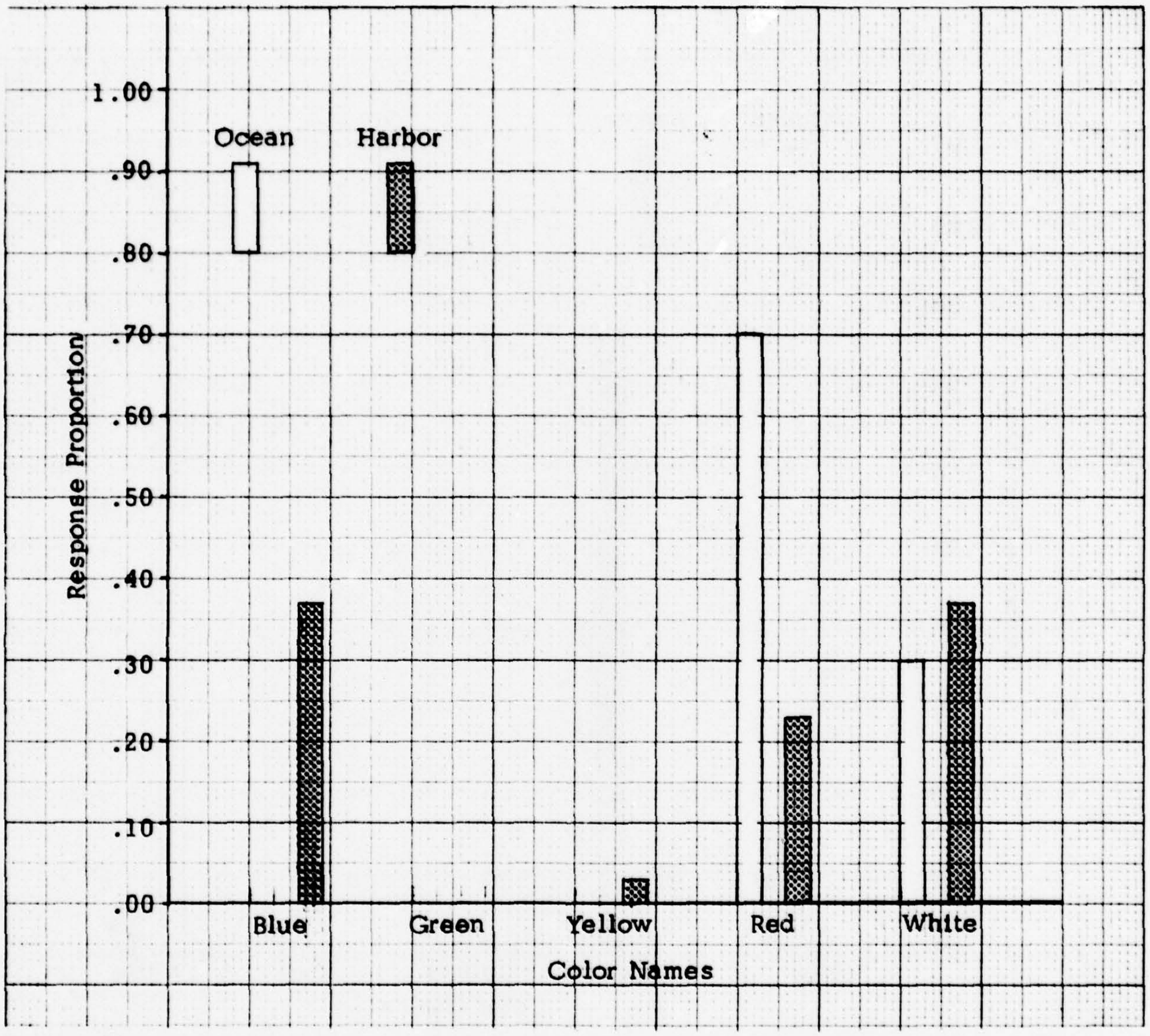

Figure 10. Distribution of Color-Name Scores in 'Ocean' vs 'Harbor' Illumination: White Display

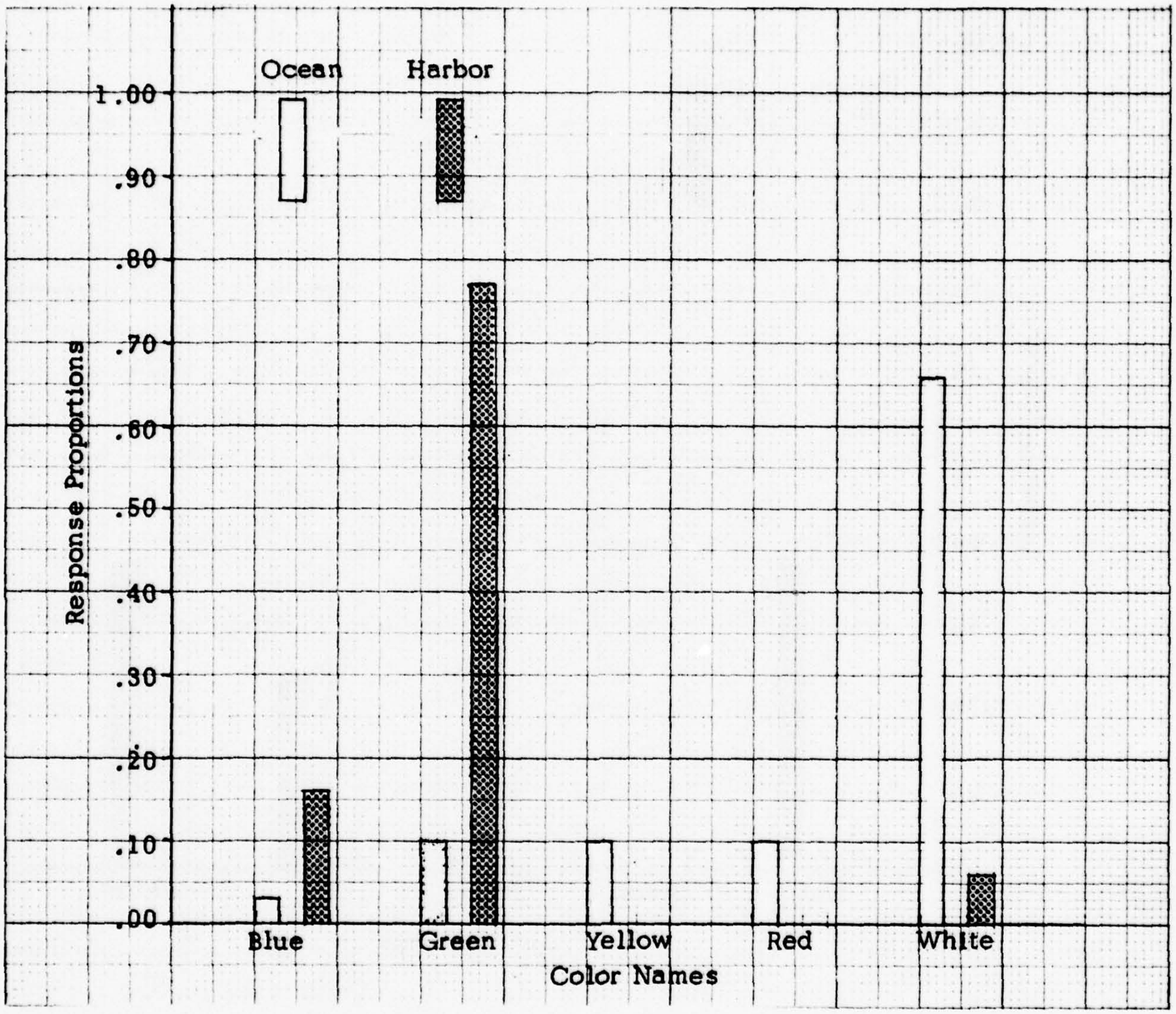

Figure 11. Distribution of Color-Name Scores in 'Ocean' vs 'Harbor' Illumination: 552 nm Display

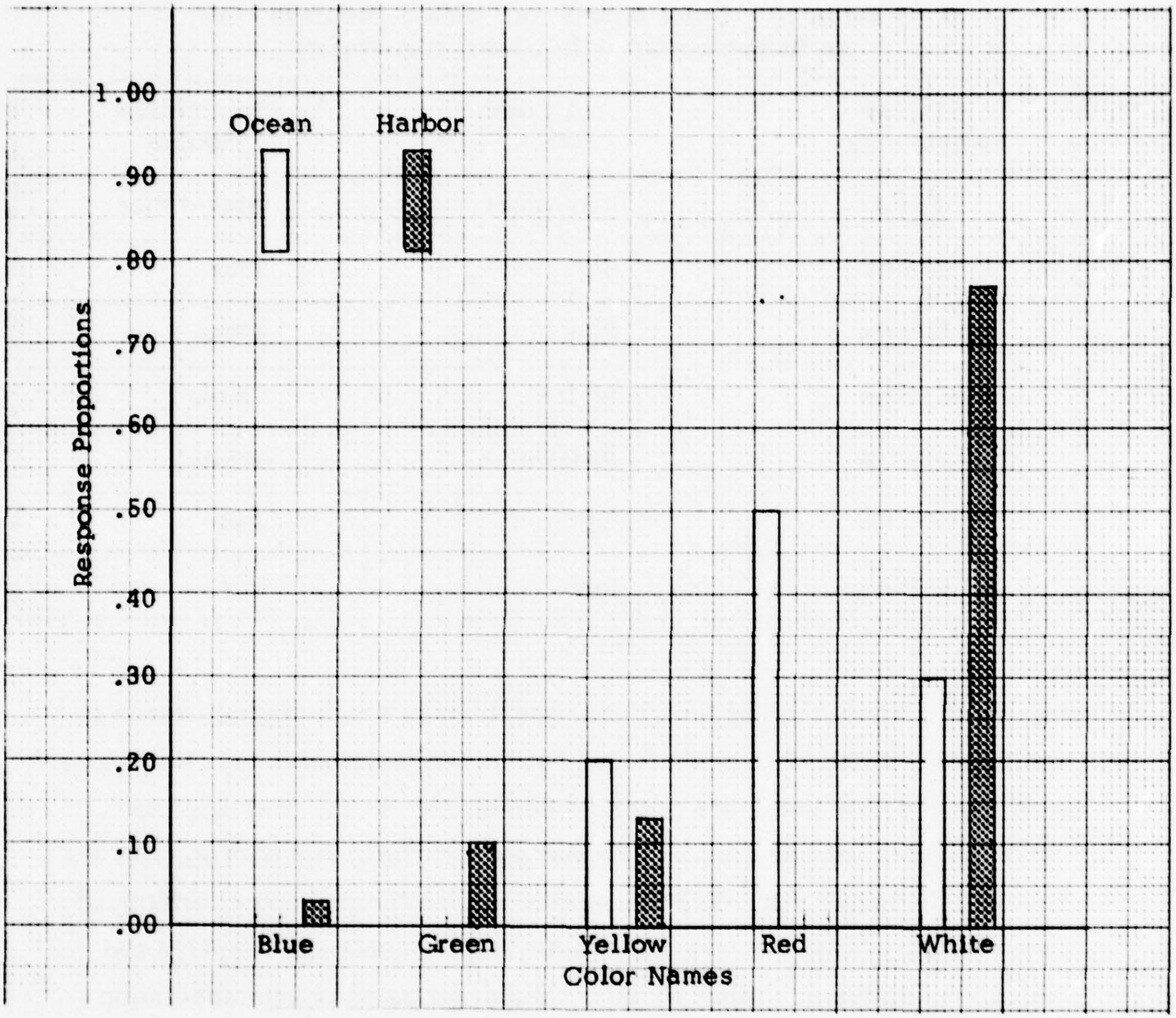

Figure 12. Distribution of Color-Name Scores in 'Ocean' vs 'Harbor' Illumination: 579 nm Display

Table 13. Color Names for Colored Displays in Homochromatically Illuminated Waters

Display Wavelength	In A Green 'Ocean'	In A Yellow 'Harbor'
White	Red-white	Blue-white
473 nm	Blue	Blue
503 nm	Blue	Blue
552 nm	White	Green
579 nm	Red-white	White
608 nm	Red	Red
640 nm	Red	Red

with depth. The region of the visible spectrum to which daylight tends is qualitatively different in oceanic and harbor/bay environments. Nearshore oceans tend to become green, inshore harbors/bays tend toward yellow. Self-luminous, colored displays viewed against these two backgrounds are dramatically different in color appearance due to the perceptual effects of chromatic adaptation. White and middle-range wavelength displays are particularly affected. Table 14 shows the differences in principal color appearance of displays which in-air would appear white, green and yellow. Display colors least affected by differences in environmental illuminance characteristic of ocean vs harbor/bay are those associated with extreme wavelength: short-wavelength displays (473-503 nm) will appear 'Blue' and long-wavelength displays (608-640 nm) will appear 'Red' in both environments.

Table 14. Display Colors Most Affected by Environmental Differences

Display Wavelength	In Air	In A Green Illuminated 'Ocean'	In A Yellow Illuminated 'Harbor'
White	White	Red	Blue
552 nm	Green	White	Green
579 nm	Yellow	Red	White

D. Completed Experiments and Technical Reports

This report describes the fifth and final experiment conducted in response to issues highlighted during the requirements analysis phase of the overall research program. These experiments investigated the effects of variations in several characteristics of self-luminous displays (luminance, size, viewing distance, wavelength and peripheral location) on three visual tasks (detection, quantitative reading and color identification) in the context of variations in important physical characteristics of natural, underwater viewing environments (turbidity and ambient light). Six technical reports contain the results of the overall program. Results of the requirements analyses are contained in the first two and results of the experiments in the last four reports listed below.

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Vaughan, W. S., and Williams, J. An analysis of environmental and perceptual determinants of display legibility underwater. Landover, Md.: Oceanautics, Inc., April 1976. (AD A026035)

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APPENDIX A

TEST PARTICIPANTS

Name	Rank/Rate	Unit
Birtz, Pierre P.	ENC	SEAL TWO
Christin, Michael P.	HM3	SEAL TWO
Fallon, John S.	EMC	SEAL TWO
Findlay, Ronald A.	GMG1	UDT-22
Folman, James J.	LT	SEAL TWO
Gant, Roger A.	MM1	SEAL TWO
Larson, Mark G.	GMG1	SEAL TWO
Pastore, Rodney L.	CEC	SEAL TWO
Pierce, Ronnie L.	RM2	UDT-22
Schwarz, Stephen A.	GMT3	UDT-21
Wysocki, Frank L.	BM1	UDT-22

APPENDIX B

PROCEDURES FOR CHARACTERIZING SPECTRAL COMPOSITION OF LIGHT ENERGY IN THE 'OCEAN' AND 'HARBOR' SIMULATIONS: ACTUAL AND CRITERION DISTRIBUTIONS

1. Estimation of Empirical Values for Relative Irradiance

Spectral distribution of the radiant energy in the water samples was approximated by first measuring the incident energy with a series of cutoff color filters and the Tektronix, Inc., J6512 irradiance probe, then carrying out a procedure with the measurements to generate relative energy per unit wavelength as plotted in the figures of the report.

Six, sharp-cutoff, absorption filters were selected which segmented the visible spectrum into five wavelength bands of approximately equal width. The filters were obtained from Schott Optical Glass, Inc., and cut to fit a filter-holding attachment of the irradiance probe. The transmittance curves for the six filters are shown in Figure A-1. Each filter transmitted energy to the right (toward the longer wavelengths) of its characteristic curve. The 50% transmittance level was used to describe the wavelength band between adjacent filters. From Figure A-1 it can be seen that the six cutoff filters defined five bands with the following wavelength boundaries at 50% transmittance:

- 425 - 475 nm
- 475 - 515 nm
- 515 - 570 nm
- 570 - 630 nm
- 630 - 700 nm

An experimental water sample was prepared and illuminated by the appropriate combination of lamps and colored acetate. Then empirical measurements of radiant energy (microwatts per square centimeter) were taken from the front of the test tank at the location of the facemask. Three measurements were made with each of the six cutoff filters and the mean value was used to characterize each filter. The energy difference between adjacent pairs of cutoff filters defined the total energy in the band of wavelengths between each filter pair. Energy per unit wavelength was calculated by dividing the

total energy by the bandwidth. Relative energy within the spectrum was calculated by setting the largest value equal to 1.0 and adjusting all other values. Relative energy was plotted in Figures 1 and 2 of the report as represented by the center wavelength of each band. Tables A-1 and A-2 provide the empirical measurements and the above-described series of calculations.

2. Derivation of Criterion Values for Relative Irradiance

Criterion values of relative irradiance per unit wavelength for the 'Ocean' and 'Harbor' simulations were derived from two sources: an estimate of the relative solar irradiance at the surface taken from the Smithsonian tables (Forsythe, 1964), and estimates of the irradiance loss coefficients at each wavelength for the two natural waters being simulated: Jerlov #5 and #9 (Jerlov, 1968). These three sets of 'givens' are tabled in Table A-3.

Since the irradiance loss coefficient (k) is per meter, the irradiance at a given water depth is calculated by the following formula:

$$I_z = (I_o)\, e^{-(k)(z)}$$

where

I_z is irradiance at depth z

I_o is irradiance at the surface

e is 2.7182818 (the natural logarithm base)

k is the loss coefficient per meter

z is depth of water

The above formula was applied to the data of Table A-3 using as values of depth (z) 20 meters for the 'Ocean' and 5 meters for the 'Harbor' simulation. Results of this procedure yielded values of irradiance at depth z for each water type and these values were then made relative by setting the largest value equal to 1.00. These values are tabled in Table A-4 and the normalized values were used to describe the criterion distributions of spectral energy for the 'Ocean' and 'Harbor' simulations as plotted in Figures 1 and 2 of the report.

3. References

Forsythe, W. S. Smithsonian Physical Tables, 9th Ed., Publication 4169, Washington: Smithsonian Institution, 1964.

Jerlov, N. G. Optical Oceanography. New York: Elsevier Oceanography Series, 5, Elsevier Scientific, 1968.

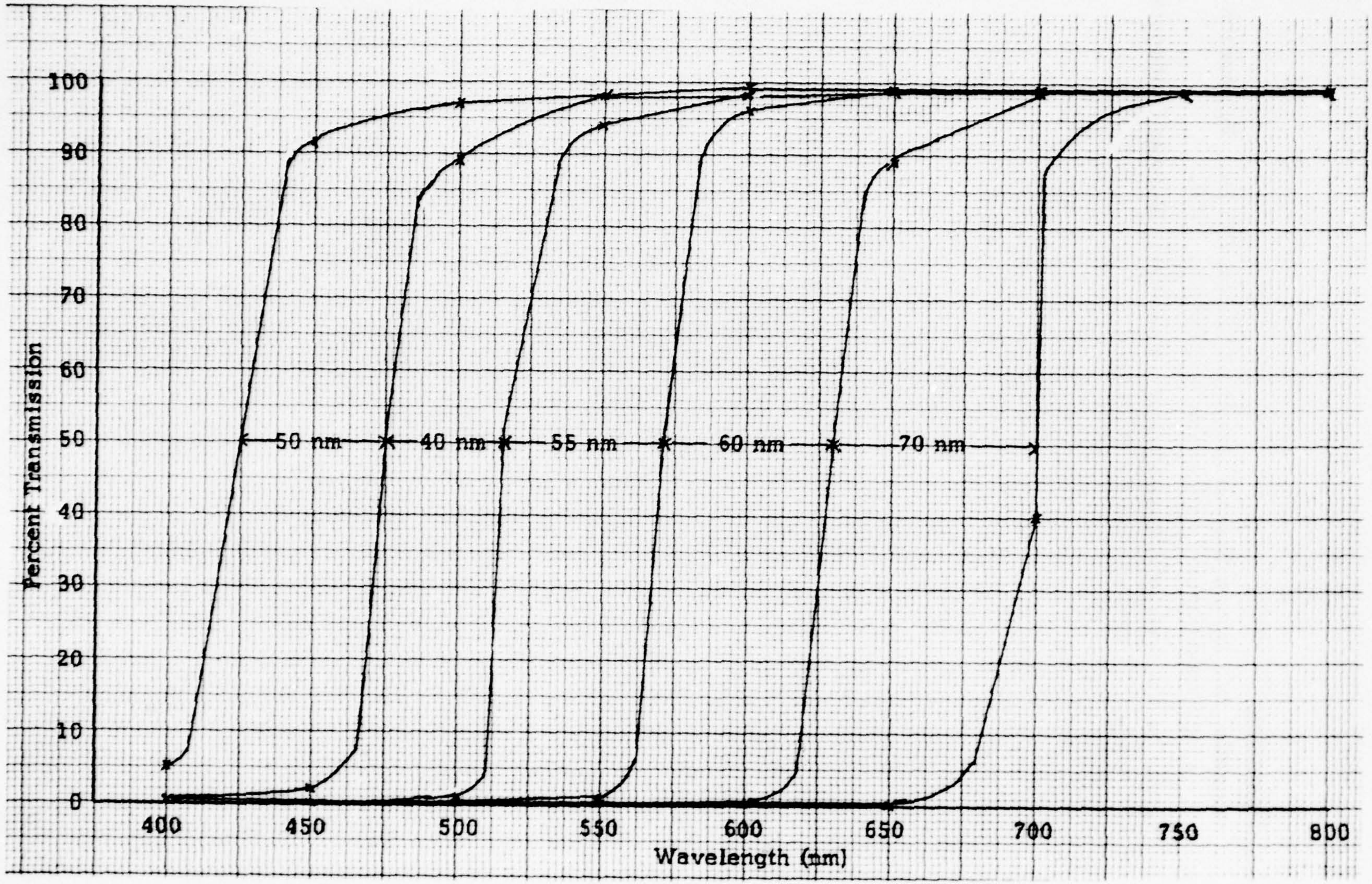

Figure B-1. Transmittance Curves of Cutoff Filters

Table B-1. Irradiance At Selected Wavelengths: 'Ocean' Simulation

Cutoff Filter No.	Measured Incident Energy (Microwatts per cm^2)	Energy Difference Between Adjacent Filters	Wavelength Difference Between Adjacent Filters	Center Wavelength of Difference Band	Absolute Energy per Unit Wavelength	Relative Energy per Unit Wavelength
GG 15	19.2					
		0.8	50 nm	450 nm	0.02	.10
GG 7	18.4					
		5.0	40 nm	495 nm	0.12	.60
OG 4	13.4					
		10.9	55 nm	542 nm	0.20	1.00
OG 2	2.5					
		1.0	60 nm	600 nm	0.02	.10
RG 2	1.5					
		0.5	70 nm	665 nm	0.007	.035
RG 8	1.0					

Table B-2. Irradiance At Selected Wavelengths: 'Harbor' Simulation

Cutoff Filter No.	Measured Incident Energy (Microwatts per cm^2)	Energy Difference Between Adjacent Filters	Wavelength Difference Between Adjacent Filters	Center Wavelength of Difference Band	Absolute Energy per Unit Wavelength	Relative Energy per Unit Wavelength
GG 15	310.0					
		2.5	50 nm	450 nm	0.05	.02
GG 7	307.5					
		12.5	40 nm	495 nm	0.31	.13
OG 4	295.0					
		117.0	55 nm	542 nm	2.13	.88
OG 2	178.0					
		144.5	60 nm	600 nm	2.41	1.00
RG 2	33.5					
		29.4	70 nm	665 nm	0.42	.17
RG 8	4.1					

Table B-3. Relative Irradiance At the Surface and Irradiance Loss Coefficients Per Wavelength for 'Ocean' and 'Harbor'

Wavelength (nm)	Relative Irradiance At the Surface	Irradiance Loss Coefficient (k) for Jerlov #5 Water	Irradiance Loss Coefficient (k) for Jerlov #9 Water
435	.638	.39	1.75
465	.905	.35	1.35
495	.998	.31	1.04
525	.995	.27	.78
555	.987	.27	.62
585	1.000	.38	.59
615	.962	.48	.63
645	.975	.56	.73
675	.875	.65	.92

Table B-4. Relative Spectral Irradiance At Selected Depths in Type 5 and Type 9 Water

Wavelength (nm)	Relative Irradiance At 20 Meters in 'Ocean' Water		Relative Irradiance At 5 Meters in 'Harbor' Water	
	Irradiance	Relative Irradiance	Irradiance	Relative Irradiance
435	2.614×10^{-4}	.058	1.010×10^{-4}	.002
465	8.253×10^{-4}	.184	1.060×10^{-3}	.020
495	2.025×10^{-3}	.451	5.506×10^{-3}	.105
525	4.494×10^{-3}	1.000	2.014×10^{-2}	.385
555	4.458×10^{-3}	.992	4.446×10^{-2}	.849
585	5.005×10^{-4}	.111	5.234×10^{-2}	1.000
615	6.520×10^{-5}	.014	4.122×10^{-2}	.788
645			2.534×10^{-2}	.484
675			8.800×10^{-3}	.168

APPENDIX C

TABLES OF RAW DATA: DISPLAY LUMINANCE VALUES (ft-L)

Table C-1. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Ocean' Illumination

Observers	White Display					
	Minimum		Clear		Limit	
	23'	41'	23'	41'	23'	41'
1	3.5	.8	17.5	3.0	49.5	34.1
2	2.4	.7	5.5	2.0	53.1	33.7
3	1.4	.5	18.2	4.8	215.4	154.0
4	1.9	1.3	18.9	7.7	156.0	173.3
5	2.3	.5	26.7	8.6	245.0	106.7
6	3.4	1.0	15.9	5.4	131.8	162.1
7	1.3	.8	36.2	4.0	136.1	39.7
8	3.9	.9	17.9	10.0	218.9	119.5
9	2.5	.8	39.0	17.1	138.3	73.5
10	3.4	2.3	19.7	11.4	237.2	50.5
$\bar{X}$	2.60	.96	21.55	7.40	158.13	94.71
σ	.92	.53	9.93	4.58	70.85	55.60

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Table C-1. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Ocean' Illumination (Continued)

Observers	473 nm Display			
	Minimum		Clear	
	23'	41'	23'	41'
1	3.6	.8	30.5	4.3
2	2.7	.9	8.1	1.9
3	2.0	.5	26.5	6.3
4	4.4	2.0	18.3	6.3
5	1.8	.3	17.0	1.7
6	1.3	.8	5.3	3.2
7	2.3	.7	27.2	2.9
8	3.4	.9	26.5	7.2
9	2.9	1.8	30.5	11.5
10	5.4	.7	18.9	4.9
$\bar{X}$	2.98	.94	20.88	5.02
σ	1.25	.54	8.94	2.96

Table C-1. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Ocean' Illumination (Continued)

Observers	503 nm Display					
	Minimum		Clear		Limit	
	23'	41'	23'	41'	23'	41'
1	3.0	1.0	22.2	5.3	106.0	18.6
2	2.7	.9	6.3	1.7	70.5	49.2
3	2.0	.6	27.4	2.0	106.0	73.5
4	6.4	1.5	16.9	6.3	106.0	76.7
5	1.5	.5	7.5	2.8	94.5	22.2
6	3.5	.8	8.8	3.0	106.0	50.0
7	1.7	.6	16.5	4.2	106.0	71.5
8	2.5	.5	11.8	5.3	74.6	45.8
9	8.9	1.8	41.4	17.4	106.0	40.2
10	3.5	1.2	10.0	4.4	28.8	23.5
$\bar{X}$	3.57	.94	16.88	5.24	90.44	47.12
σ	2.33	.44	10.95	4.53	25.64	21.65

Table C-1. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Ocean' Illumination (Continued)

Observers	552 nm Display					
	Minimum		Clear		Limit	
	23'	41'	23'	41'	23'	41'
1	2.7	.7	12.7	3.2	100.3	33.3
2	2.7	1.4	9.0	4.7	38.5	15.1
3	2.0	.5	29.6	5.1	170.6	40.7
4	1.9	1.6	18.5	9.2	44.4	28.4
5	1.9	.5	14.9	2.5	118.3	20.5
6	2.4	2.6	20.5	14.9	116.5	72.9
7	2.1	.6	29.3	9.8	305.0	29.0
8	2.6	.7	14.0	5.8	80.0	42.9
9	2.4	1.3	22.6	8.3	79.0	28.4
10	3.6	.7	9.9	2.1	26.5	8.3
$\bar{X}$	2.43	1.06	18.10	6.56	107.91	31.95
σ	.52	.67	7.38	4.00	81.72	17.90

Table C-1. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Ocean' Illumination (Continued)

Observers	579 nm Display					
	Minimum		Clear		Limit	
	23'	41'	23'	41'	23'	41'
1	3.2	.7	19.3	3.9	298.1	22.0
2	1.8	.9	5.0	2.5	38.3	15.5
3	1.7	.7	11.3	5.1	43.3	63.5
4	3.1	.5	14.8	6.4	328.1	47.6
5	1.9	.7	33.2	3.5	279.3	43.3
6	2.9	3.8	8.7	16.2	70.1	88.5
7	1.3	.5	19.1	5.4	112.5	38.3
8	1.7	1.7	11.4	6.7	106.6	42.4
9	2.5	1.1	20.7	6.7	332.0	95.8
10	1.7	.7	4.6	2.6	58.8	9.5
$\bar{X}$	2.18	1.13	14.81	5.90	166.71	46.64
σ	.68	1.00	8.65	3.95	125.86	28.88

Table C-1. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Ocean' Illumination (Continued)

Observers	608 nm Display					
	Minimum		Clear		Limit	
	23'	41'	23'	41'	23'	41'
1	2.3	.6	15.1	3.3	123.2	21.3
2	2.4	.9	6.9	2.5	59.4	7.8
3	1.2	.8	14.9	8.7	45.0	49.1
4	1.4	.7	11.5	5.9	72.1	30.5
5	1.4	.7	16.8	2.2	180.5	15.6
6	2.0	.9	6.5	3.9	60.8	26.6
7	1.3	.6	14.7	2.8	106.6	36.4
8	1.9	.7	9.9	5.3	54.8	26.0
9	1.9	.8	16.8	3.2	118.4	25.0
10	2.5	1.9	8.9	7.1	30.5	33.2
$\bar{X}$	1.83	.86	12.20	4.49	85.13	27.15
σ	.48	.38	3.97	2.18	46.01	11.37

Table C-1. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Ocean' Illumination (Continued)

Observers	640 nm Display					
	Minimum		Clear		Limit	
	23'	41'	23'	41'	23'	41'
1	4.9	1.0	24.7	5.0	189.0	24.5
2	2.2	1.2	7.5	3.0	28.9	16.7
3	1.6	.7	14.5	8.0	33.5	40.4
4	2.9	.8	14.0	6.8	61.1	32.9
5	1.3	.5	28.6	6.2	142.7	31.7
6	2.7	.9	8.2	4.6	64.3	28.0
7	1.6	.5	14.5	2.8	189.0	28.6
8	2.6	.6	12.3	4.0	48.8	21.2
9	4.1	1.1	21.0	17.7	85.4	26.2
10	2.7	1.0	7.1	4.9	20.8	21.8
$\bar{X}$	2.66	.83	15.24	6.30	86.35	27.20
σ	1.13	.25	7.36	4.32	64.27	6.78

Table C-2. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Harbor' Illumination

Observers	White Display				473 nm Display		
	Minimum		Clear		Minimum		Clear
	41'	82'	41'	82'	41'	82'	82'
1	2482	1189	13983	2941	1477	586	2158
2	2582	2246	6469	4583	1311	1000	2158
3	3908	730	11623	1469	1177	380	2235
4	1834	936	8166	2293	2053	384	1359
5	2741	698	9346	1854	744	418	1598
6	3036	1307	5098	4213	913	501	1573
7	4109	1094	7374	2339	2158	834	2235
8	2482	531	20011	4529	1288	406	2235
9	2019	1307	2973	2741	2137	849	2350
10	1691	788	3763	2880	1784	982	2350
$\bar{X}$	2688	1083	8881	2984	1504	634	2025
σ	809.56	488.81	5181.72	1105.12	508.45	255.37	366.53

Table C-2. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Harbor' Illumination (Continued)

Observers	503 nm Display				552 nm Display			
	Minimum		Clear		Minimum		Clear	
	41'	82'	41'	82'	41'	82'	41'	82'
1	6317	1478	8010	4630	3309	1073	16297	5379
2	7426	2083	9023	5103	11761	4194	20524	7314
3	3435	1392	9350	4721	4362	1873	10360	3704
4	2736	1392	9303	4052	4362	1433	10197	8841
5	2050	1113	6617	2406	2807	1371	9723	2807
6	3921	2406	9303	4630	2200	2485	10865	4597
7	3162	1640	7810	3435	2458	1275	4597	3266
8	2003	953	9303	6932	2377	1604	14199	10525
9	7040	3268	8931	7333	11215	1482	15140	4908
10	3669	1375	9303	9303	2129	1417	5643	3794
$\bar{X}$	4176	1710	8695	5255	4698	1821	11755	5514
σ	2015.60	695.51	921.44	2040.77	3671.70	919.58	4863.06	2566.04

Table C-2. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Harbor' Illumination (Continued)

Observers	579 nm Display				608 nm Display			
	Minimum		Clear		Minimum		Clear	
	41'	82'	41'	82'	41'	82'	41'	82'
1	4260	1564	7535	3933	3340	1252	5951	6344
2	5337	3139	11437	5418	2736	2970	6449	4984
3	5257	1900	15332	4877	4853	1841	12315	5281
4	4204	1005	7535	2218	2643	896	6449	3076
5	3369	900	5929	2099	1841	664	3587	1906
6	2959	2724	15605	8421	3503	2970	11097	8373
7	4951	941	8158	2008	3630	927	5776	2411
8	1986	747	9870	5668	1778	1262	11291	5050
9	1694	2822	3369	4390	4195	1589	7115	3040
10	1233	941	3369	2599	2094	1698	7000	3150
$\bar{X}$	3525	1668	8814	4163	3061	1607	7703	4362
σ	1514.26	919.54	4319.45	2047.17	1024.38	808.37	2855.26	2011.91

Table C-2. Luminance Requirements (ft-L) for Legibility of Seven Colored Displays in 'Harbor' Illumination (Continued)

Observers	640 nm Display			
	Minimum		Clear	
	41'	82'	41'	82'
1	2308	1056	3910	4458
2	3330	1843	11449	3330
3	2459	831	12066	1843
4	2397	1739	7557	2194
5	2620	542	7557	1680
6	3742	993	10891	3797
7	6428	858	13055	2007
8	2554	858	10497	5124
9	3090	1801	6090	2824
10	1034	650	2660	1386
$\bar{X}$	2996	1117	8573	2864
σ	1404.84	490.53	3567.95	1271.47

APPENDIX D

TABLES OF RAW DATA: COLOR-NAME SCORES

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment

1. Color Appearance of A White Stimulus

Observer	Small Digit Size: 3 mm at 45 cm (23')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1	2				1	2				1	3				
2	1				2	1				2	3				
3	1				2	1				2	2				1
4					3					3	3				
5					3					3	3				
6					3		1			2	1				2
7	1				2	1				2	3				
8	2				1	2				1	2				1
9					3	1				2	1				2
10					3					3					3
Total	7				23	8	1			21	21				9
p	.23				.77	.27	.03			.70	.70				.30

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

1. Color Appearance of A White Stimulus (Continued)

Observer	Large Digit Size: 3 mm at 25 cm (41')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1					3	2				1	2				1
2	2				1	2				1	3				
3					3					3	1				2
4					3					3	3				
5					3					3	3				
6					3	1				2	1				2
7	1				2	1				2	2				1
8	2				1	2				1	2				1
9					3	1				2	1				2
10					3					3					3
Total	5				25	9				21	18				12
p	.16				.83	.30				.70	.60				.40

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

2. Color Appearance of 473 nm Stimulus

Observer	Small Digit Size: 3 mm at 45 cm (23')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1		3					3								
2		3					3								
3		3				1	2								
4		3					3								
5		3					3								
6		3					3								
7		3				1	2								
8		3					2			1					
9		3					3								
10		3					3								
Total		30				2	27			1					
p		1.00				.06	.90			.03					

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

2. Color Appearance of 473 nm Stimulus (Continued)

Observer	Large Digit Size: 3 mm at 25 cm (41')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1		3				1	2								
2		3					3								
3		3					3								
4		3					3								
5		3					3								
6		3					3								
7		2	1				2	1							
8		3					3								
9		3					3								
10		3					3								
Total		29	1			1	28	1							
p		.97	.03			.03	.93	.03							

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

3. Color Appearance of 503 nm Stimulus

Observer	Small Digit Size: 3 mm at 45 cm (23')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1	1	2				1	2				1	2			
2			3					3			1		2		
3	1	2				1	2				1	2			
4		3					3					3			
5		3					3					3			
6		2	1				3					3			
7		3					3				1	2			
8		2	1				3					3			
9		3					3					3			
10		3					3					3			
Total	2	23	5			2	25	3			4	24	2		
p	.06	.77	.16			.06	.83	.10			.13	.80	.06		

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

3. Color Appearance of 503 nm Stimulus (Continued)

Observer	Large Digit Size: 3 mm at 25 cm (41')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1	1	2				1	2				1	2			
2			3					3					3		
3	1	2				1	2				1	2			
4		3					3					3			
5		3					3					3			
6		2	1				3					2	1		
7		2	1			1	2				2	1			
8		3					3				1	2			
9		3					3					3			
10		3					3				1	2			
Total	2	23	5			3	24	3			6	20	4		
p	.06	.77	.16			.10	.80	.10			.20	.66	.13		

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

4. Color Appearance of 552 nm Stimulus

Observer	Small Digit Size: 3 mm at 45 cm (23')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1	3					3					2		1		
2	1		2			2		1			2		1		
3	3					2		1						3	
4	3					3					3				
5	3					3								3	
6			3					3					2	1	
7		1			2	2		1						3	
8			1	2		2			1					3	
9	3					3					3				
10	3									3	1				2
Total	19	1	6	2	2	20		6	1	3	11		4	13	2
p	.63	.03	.20	.06	.06	.66		.20	.03	.10	.37		.13	.43	.06

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

4. Color Appearance of 552 nm Stimulus (Continued)

Observer	Large Digit Size: 3 mm at 25 cm (41')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1	2		1			2		1			2		1		
2	2	1				2	1				2	1			
3	2			1		2			1					3	
4	3					3					3				
5	3					3								3	
6			2	1				1	2				1	2	
7	2				1	2		1						3	
8	2				1	3					3				
9	2				1	3					2		1		
10					3					3	1				2
Total	18	1	3	2	6	20	1	3	3	3	13	1	3	11	2
p	.60	.03	.10	.06	.20	.66	.03	.10	.10	.10	.43	.03	.10	.37	.06

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

5. Color Appearance of 579 nm Stimulus

Observer	Small Digit Size: 3 mm at 45 cm (23')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1	2		1			3					3				
2	1				2	2				1	3				
3	1				2				3					3	
4					3	3					3				
5					3				3					3	
6					3				3					2	1
7	1				2	3					3				
8	1				2	2				1				2	1
9					3	1				2	3				
10					3					3					3
Total	6		1		23	14			9	7	15			10	5
p	.20		.03		.77	.46			.30	.23	.50			.33	.16

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

5. Color Appearance of 579 nm Stimulus (Continued)

Observer	Large Digit Size: 3 mm at 25 cm (41')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1	2				1	2				1	2				1
2	3					3					3				
3				1	2				3					3	
4					3					3	3				
5					3					3					3
6				1	2				1	2				1	2
7	1				2	2				1				3	
8	2				1	1			2					3	
9					3	1				2	3				
10					3					3					3
Total	8			2	20	9			6	15	11			10	9
p	.27			.06	.66	.30			.20	.50	.37			.33	.30

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

6. Color Appearance of 608 nm Stimulus

Observer	Small Digit Size: 3 mm at 45 cm (23')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1					3	1				2	1				2
2					3					3	2				1
3					3					3					3
4					3					3					3
5					3					3					3
6					3					3					3
7					3					3		1			2
8					3					3					3
9					3					3					3
10					3					3					3
Total					30	1				29	3	1			26
p					1.00	.03				.97	.10	.03			.86

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

6. Color Appearance of 608 nm Stimulus (Continued)

Observer	Large Digit Size: 3 mm at 25 cm (41')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1					3					3					3
2					3					3	3				
3					3					3					3
4					3					3					3
5					3					3					3
6					3					3	1				2
7					3					3	1				2
8					3					3					3
9					3					3					3
10					3					3					3
Total					30					30	5				25
p					1.00					1.00	.16				.83

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

7. Color Appearance of 640 nm Stimulus

Observer	Small Digit Size: 3 mm at 45 cm (23')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1					3					3					3
2					3					3	3				
3					3					3					3
4					3					3					3
5					3					3					3
6					3					3		1			2
7					3					3	1				2
8					3					3					3
9					3					3					3
10					3					3					3
Total					30					30	4	1			25
p					1.00					1.00	.13	.03			.83

Table D-1. Color Appearance Scores for Seven Wavelengths At Three Levels of Luminance in 'Ocean' Viewing Environment (Continued)

7. Color Appearance of 640 nm Stimulus (Continued)

Observer	Large Digit Size: 3 mm at 25 cm (41')														
	Minimum Legibility					Clear Legibility					Limit Legibility				
	W	B	G	Y	R	W	B	G	Y	R	W	B	G	Y	R
1					3					3					3
2					3					3	3				
3					3					3					3
4					3					3					3
5					3					3					3
6					3		1			2		1			2
7					3					3	1				2
8					3					3					3
9					3					3					3
10					3					3					3
Total					30		1			29	4	1			25
p					1.00		.03			.97	.13	.03			.83

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment

1. Color Appearance of A White Stimulus

Observer	Small Digit Size: 3 mm at 25 cm (41')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	2		1			2		1		
2	1	2				1	2			
3	3					3				
4	1				2	1				2
5	1	2				1	2			
6		2			1		1			2
7		2			1		2			1
8		2			1		2			1
9	3					3				
10	1				2	1				2
Total	12	10	1		7	12	9	1		8
p	.40	.33	.03		.23	.40	.30	.03		.27

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

1. Color Appearance of A White Stimulus (Continued)

Observer	Large Digit Size: 6 mm at 25 cm (82')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	2	1				2	1			
2	2	1				2	1			
3	1	2				2	1			
4	1				2				1	2
5	1	2				1	2			
6		2			1		2			1
7		2			1		2			1
8	2				1	2				1
9	1	2				1	2			
10	1				2	1				2
Total	11	12			7	11	11		1	7
p	.37	.40			.23	.37	.37		.03	.23

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

2. Color Appearance of 473 nm Stimulus

Observer	Small Digit Size: 3 mm at 25 cm (41')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1		3								
2		3								
3	1	2								
4		3								
5		3								
6		3								
7		3								
8		3								
9		3								
10		3								
Total	1	29								
p	.03	.97								

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

2. Color Appearance of 473 nm Stimulus (Continued)

Observer	Large Digit Size: 6 mm at 25 cm (82')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1		3					3			
2		3					3			
3		3					3			
4		3					3			
5		3					3			
6		3					3			
7		2			1		2			1
8		2			1		3			
9		3					3			
10		3					3			
Total		28			2		29			1
p		.93			.06		.97			.03

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

3. Color Appearance of 503 nm Stimulus

Observer	Small Digit Size: 3 mm at 25 cm (41')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	1	2				1	2			
2		3					3			
3		3				1	2			
4		3					3			
5		3					3			
6		3					3			
7		3					3			
8		3					3			
9		3					3			
10		3					3			
Total	1	29				2	28			
p	.03	.97				.06	.93			

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

3. Color Appearance of 503 nm Stimulus (Continued)

Observer	Large Digit Size: 6 mm at 25 cm (82')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	1	2				1	2			
2		3					3			
3		3				1	2			
4		3					3			
5		3					3			
6		3					3			
7		3					3			
8	1	2					3			
9		3					3			
10	1	2					3			
Total	3	27				2	28			
p	.10	.90				.06	.93			

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

4. Color Appearance of 552 nm Stimulus

Observer	Small Digit Size: 3 mm at 25 cm (41')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1			3					3		
2			3					3		
3			3					3		
4			3					3		
5		3				1	2			
6		1	2				1	2		
7		1	2				1	2		
8	1		2					3		
9			3					3		
10		3					3			
Total	1	8	21			1	7	22		
p	.03	.27	.70			.03	.23	.73		

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

4. Color Appearance of 552 nm Stimulus (Continued)

Observer	Large Digit Size: 6 mm at 25 cm (82')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1			3					3		
2			3					3		
3	1		2					3		
4		3					3			
5	1		2			1		2		
6			3					3		
7		1	2					3		
8		1	2					3		
9			3					3		
10	1	2				1	2			
Total	3	7	20			2	5	23		
p	.10	.23	.66			.06	.16	.77		

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

5. Color Appearance of 579 nm Stimulus

Observer	Small Digit Size: 3 mm at 25 cm (41')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	2		1			2		1		
2	3					3				
3	3					3				
4	3					3				
5	3					3				
6			3					3		
7	2	1				2	1			
8	2			1		2			1	
9			3					3		
10	2				1	2				1
Total	20	1	7	1	1	20	1	7	1	1
p	.66	.03	.23	.03	.03	.66	.03	.23	.03	.03

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

5. Color Appearance of 579 nm Stimulus (Continued)

Observer	Large Digit Size: 6 mm at 25 cm (82')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	3					3				
2	3					3				
3	3					2			1	
4	3					3				
5	3					3				
6			3					3		
7	2				1	3				
8	3					3				
9				3					3	
10	3					3				
Total	23		3	3	1	23		3	4	
p	.77		.10	.10	.03	.77		.10	.13	

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

6. Color Appearance of 608 nm Stimulus

Observer	Small Digit Size: 3 mm at 25 cm (41')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	1				2	1				2
2					3					3
3	2			1		1				2
4					3					3
5					3					3
6		1			2		1			2
7		1			2		1			2
8	1				2	1				2
9	1				2	1				2
10					3					3
Total	5	2		1	22	4	2			24
p	.16	.06		.03	.73	.13	.06			.80

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

6. Color Appearance of 608 nm Stimulus (Continued)

Observer	Large Digit Size: 6 mm at 25 cm (82')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	1				2	1				2
2					3					3
3	1				2	1				2
4					3					3
5					3					3
6		1			2		1			2
7					3					3
8	1				2	1				2
9	1				2	1				2
10					3					3
Total	4	1			25	4	1			25
p	.13	.03			.83	.13	.03			.83

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

7. Color Appearance of 640 nm Stimulus

Observer	Small Digit Size: 3 mm at 25 cm (41')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	1				2	1				2
2					3					3
3	1				2	1				2
4					3					3
5		2			1		1			2
6					3					3
7		1			2		1			2
8					3					3
9		1			2		1			2
10					3					3
Total	2	4			24	2	3			25
p	.06	.13			.80	.06	.10			.83

Table D-2. Color Appearance Scores for Seven Wavelengths At Two Levels of Luminance in 'Harbor' Viewing Environment (Continued)

7. Color Appearance of 640 nm Stimulus (Continued)

Observer	Large Digit Size: 6 mm at 25 cm (82')									
	Minimum Legibility					Clear Legibility				
	W	B	G	Y	R	W	B	G	Y	R
1	1				2					3
2					3					3
3					3					3
4					3					3
5					3					3
6		1			2		1			2
7		1			2		1			2
8					3					3
9		1			2		1			2
10					3					3
Total	1	3			26		3			27
p	.03	.10			.86		.10			.90

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